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FORM PTO-1390 (Modified) (REV 11-98) U.S. DEPARTMENT OF COMMERCE PATENT AND TRADEMARK OFFICE **TRANSMITTAL LETTER TO THE UNITED STATES DESIGNATED/ELECTED OFFICE (DO/EO/US) CONCERNING A FILING UNDER 35 U.S.C. 371**		ATTORNEY'S DOCKET NUMBER **DP-548US** U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.5) 09/807823
INTERNATIONAL APPLICATION NO. **PCT/JP99/05678**	INTERNATIONAL FILING DATE **October 14, 1999**	PRIORITY DATE CLAIMED **October 20, 1998**

TITLE OF INVENTION
METHOD FOR DRIVING INK JET RECORDING HEAD

APPLICANT(S) FOR DO/EO/US
Masakazu Okuda

Applicant herewith submits to the United States Designated/Elected Office (DO/EO/US) the following items and other information:

1. ☒ This is a **FIRST** submission of items concerning a filing under 35 U.S.C. 371.
2. ☐ This is a **SECOND** or **SUBSEQUENT** submission of items concerning a filing under 35 U.S.C. 371
3. ☒ This is an express request to begin national examination procedures (35 U.S.C. 371(f)) at any time rather than delay examination until the expiration of the applicable time limit set in 35 U.S.C. 371(b) and PCT Articles 22 and 39(1).
4. ☒ A proper Demand for International Preliminary Examination was made by the 19th month from the earliest claimed priority date
5. ☒ A copy of the International Application as filed (35 U.S.C. 371 (c) (2))
   - a. ☐ is transmitted herewith (required only if not transmitted by the International Bureau).
   - b. ☒ has been transmitted by the International Bureau.
   - c. ☐ is not required, as the application was filed in the United States Receiving Office (RO/US).
6. ☒ A translation of the International Application into English (35 U.S C. 371(c)(2)).
7. ☒ A copy of the International Search Report (PCT/ISA/210).
8. ☒ Amendments to the claims of the International Application under PCT Article 19 (35 U.S.C. 371 (c)(3))
   - a. ☐ are transmitted herewith (required only if not transmitted by the International Bureau)
   - b. ☐ have been transmitted by the International Bureau.
   - c. ☐ have not been made; however, the time limit for making such amendments has NOT expired.
   - d. ☒ have not been made and will not be made.
9. ☐ A translation of the amendments to the claims under PCT Article 19 (35 U.S.C. 371(c)(3)).
10. ☒ An oath or declaration of the inventor(s) (35 U.S.C. 371 (c)(4)).
11. ☒ A copy of the International Preliminary Examination Report (PCT/IPEA/409).
12. ☒ A translation of the annexes to the International Preliminary Examination Report under PCT Article 36 (35 U.S.C. 371 (c)(5)).

Items 13 to 20 below concern document(s) or information included:

13. ☒ An Information Disclosure Statement under 37 CFR 1.97 and 1.98.
14. ☐ An assignment document for recording. A separate cover sheet in compliance with 37 CFR 3.28 and 3.31 is included.
15. ☒ A **FIRST** preliminary amendment.
16. ☐ A **SECOND** or **SUBSEQUENT** preliminary amendment.
17. ☐ A substitute specification.
18. ☐ A change of power of attorney and/or address letter.
19. ☐ Certificate of Mailing by Express Mail
20. ☒ Other items or information:

International Publication WO00/23278 (cover page) 17 sheets of formal drawings (Figs 1-17)
Form PCT/RO/105 (7/98)
Form PCT/ISA/202 (7/98)
PCT-Easy Version 2.83 (original request)
03-3454-1111 (10/20/98)
Form PCT/1B/301 (July 1998) Notification of Receipt of Record Copy
Form PCT/1B/304 (July 1998) Notification Concerning Submission or Transmittal of PriorityDocument
Form PCT/1B/308 (July 1996) Notice Informing the Applicant of the Comm. of the Int'l App. to the Designated Offices
Form PCT/1B/332 (September 1997) Information Concerning Elected Offices Notified of their Election
Form PCT/1B338 (July 1996) Notification of Transmittal of Copies of Trans. of the Int'l Preliminary Examination Rpt.

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U.S. APPLICATION NO. (IF KNOWN, SEE 37 CFR 1.5) 09/807823	INTERNATIONAL APPLICATION NO. PCT/JP99/05678	ATTORNEY'S DOCKET NUMBER DP-548US

21. The following fees are submitted:.

BASIC NATIONAL FEE (37 CFR 1.492 (a) (1) - (5)) :

	CALCULATIONS	PTO USE ONLY
☐ Neither international preliminary examination fee (37 CFR 1.482) nor international search fee (37 CFR 1.445(a)(2) paid to USPTO and International Search Report not prepared by the EPO or JPO **$1,000.00**		
☒ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but Internation Search Report prepared by the EPO or JPO **$860.00**		
☐ International preliminary examination fee (37 CFR 1.482) not paid to USPTO but international search fee (37 CFR 1.445(a)(2)) paid to USPTO **$710.00**		
☐ International preliminary examination fee paid to USPTO (37 CFR 1.482) but all claims did not satisfy provisions of PCT Article 33(1)-(4) **$690.00**		
☐ International preliminary examination fee paid to USPTO (37 CFR 1.482) and all claims satisfied provisions of PCT Article 33(1)-(4) **$100.00**		
ENTER APPROPRIATE BASIC FEE AMOUNT =	**$860.00**	
Surcharge of **$130.00** for furnishing the oath or declaration later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (e)).	**$0.00**	

CLAIMS	NUMBER FILED	NUMBER EXTRA	RATE		
Total claims	17 - 20 =	0	x $18.00	**$0.00**	
Independent claims	1 - 3 =	0	x $80.00	**$0.00**	
Multiple Dependent Claims **(check if applicable).**			☐	**$0.00**	
TOTAL OF ABOVE CALCULATIONS			=	**$860.00**	
Reduction of 1/2 for filing by small entity, if applicable. Verified Small Entity Statement must also be filed (Note 37 CFR 1.9, 1.27, 1.28) **(check if applicable).**			☐	**$0.00**	
SUBTOTAL			=	**$860.00**	
Processing fee of **$130.00** for furnishing the English translation later than ☐ 20 ☐ 30 months from the earliest claimed priority date (37 CFR 1.492 (f)).			+	**$0.00**	
TOTAL NATIONAL FEE			=	**$860.00**	
Fee for recording the enclosed assignment (37 CFR 1.21(h)). The assignment must be accompanied by an appropriate cover sheet (37 CFR 3.28, 3.31) **(check if applicable).**			☒	**$40.00**	
TOTAL FEES ENCLOSED			=	**$900.00**	
				Amount to be: refunded	$
				charged	$

☒ A check in the amount of **$900.00** to cover the above fees is enclosed.

☐ Please charge my Deposit Account No. in the amount of to cover the above fees. A duplicate copy of this sheet is enclosed.

☒ The Commissioner is hereby authorized to charge any fees which may be required, or credit any overpayment to Deposit Account No. **50-0481** A duplicate copy of this sheet is enclosed.

NOTE: Where an appropriate time limit under 37 CFR 1.494 or 1.495 has not been met, a petition to revive (37 CFR 1.137(a) or (b)) must be filed and granted to restore the application to pending status.

SEND ALL CORRESPONDENCE TO:

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NAME

34,386

REGISTRATION NUMBER

April 19, 2001

DATE

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DP-548US

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

In re patent application of

Masakazu Okuda

Serial No.: Not Yet Assigned | Group Art Unit: Not Yet Assigned

Filing Date: Concurrently Herewith | Examiner: Unknown

For: METHOD FOR DRIVING INK JET RECORDING HEAD

Assistant Commissioner of Patents
Washington, D.C. 20231

PRELIMINARY AMENDMENT

Sir:

Prior to examination on the merits and calculation of the filing fee, please amend the above-identified application as follows:

IN THE CLAIMS:

Please amend the claims as follows:

3. (Amended) The method for driving an ink jet recording head according to claim 1, characterized in that the voltage waveform of said driving voltage includes a fourth voltage changing process for applying a voltage in a direction that reduces the voltage of said pressure generating chamber, after said first voltage changing process, said second voltage changing process, and said third voltage changing process.

5. (Amended) The method for driving an ink jet recording head according to claim 3, characterized in that a time interval between a start time of said second voltage changing process and a start time of said fourth voltage changing process is set substantially half the length of the resonance frequency T_c of the pressure wave generated in said pressure generating chamber.

6. (Amended) The method for driving an ink jet recording head according to claim 1, characterized in that said electromechanical converter comprises a piezoelectric actuator.

7. (Amended) The method for driving an ink jet recording head according to claim 1, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

Please add claims 8-17 as follows:

-- 8. (New) The method for driving an ink jet recording head according to claim 2, characterized in that the voltage waveform of said driving voltage includes a fourth voltage changing process for applying a voltage in a direction that reduces the voltage of said pressure generating chamber, after said first voltage changing process, said second voltage changing process, and said third voltage changing process.

9. (New) The method for driving an ink jet recording head according to claim 4, characterized in that a time interval between a start time of said second voltage changing process and a start time of said fourth voltage changing process is set substantially half the length of the resonance frequency T_c of the pressure wave generated in said pressure generating chamber.

10. (New) The method for driving an ink jet recording head according to claim 2, characterized in that said electromechanical converter comprises a piezoelectric actuator.

11. (New) The method for driving an ink jet recording head according to claim 3, characterized in that said electromechanical converter comprises a piezoelectric actuator.

12. (New) The method for driving an ink jet recording head according to claim 4, characterized in that said electromechanical converter comprises a piezoelectric actuator.

13. (New) The method for driving an ink jet recording head according to claim 5, characterized in that said electromechanical converter comprises a piezoelectric actuator.

14. (New) The method for driving an ink jet recording head according to claim 2, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

15. (New) The method for driving an ink jet recording head according to claim 3, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

16. (New) The method for driving an ink jet recording head according to claim 4, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

17. (New) The method for driving an ink jet recording head according to claim 5, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size. - -

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REMARKS

Claims 3, 5, 6 and 7 have been amended to delete multiple-dependency and claims 8 - 17 have been added accordingly.

Attached hereto is a marked-up version of the changes made to the claims by the current Amendment. The attached pages are captioned **"<u>Version with markings to show changes made.</u>"**

Early, favorable prosecution on the merits is respectfully requested.

Please charge any deficiencies in fees and credit any overpayment of fees to Attorney's Deposit Account No. 50-0481.

Respectfully submitted,

Sean M. McGinn
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Date: 4/19/01

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VERSION WITH MARKINGS TO SHOW CHANGES MADE

In the claims:

3. (Amended) The method for driving an ink jet recording head according to claim 1 [or 2], characterized in that the voltage waveform of said driving voltage includes a fourth voltage changing process for applying a voltage in a direction that reduces the voltage of said pressure generating chamber, after said first voltage changing process, said second voltage changing process, and said third voltage changing process.

5. (Amended) The method for driving an ink jet recording head according to claim 3 [or 4], characterized in that a time interval between a start time of said second voltage changing process and a start time of said fourth voltage changing process is set substantially half the length of the resonance frequency T_c of the pressure wave generated in said pressure generating chamber.

6. (Amended) The method for driving an ink jet recording head according to [any of] claim[s] 1 [to 5], characterized in that said electromechanical converter [is] <u>comprises</u> a piezoelectric actuator.

7. (Amended) The method for driving an ink jet recording head according to [any of] claim[s] 1 [to 5], characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

17/PRTS

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SPECIFICATION

METHOD FOR DRIVING INK JET RECORDING HEAD

TECHNICAL FIELD

The present invention relates to a method for driving an ink jet recording head which method ejects fine ink droplets through a nozzle to record characters or images.

BACKGROUND ART

One of such recording heads, what is called an on-demand ink jet recording head that ejects ink droplets through a nozzle depending on printed information, is conventionally commonly known (for example, see Japanese Patent Publication No. SHO 53-12138). Figure 15 is a sectional view schematically showing a basic configuration of one of such on-demand ink jet recording heads which is called a Kyser type.

In this Kyser type recording head, on an ink upstream side, a pressure generating chamber 91 and a common ink chamber 92 are connected together via an ink supply hole (ink supply passage) 93, and on an ink downstream side, the pressure generating chamber 91 and a nozzle 94 are connected together, as shown in Figure 15. Additionally, a bottom plate portion of the pressure generating section 91, which is located at the bottom of Figure 15, comprises a diaphragm 95 having a piezoelectric actuator 96 on its rear surface.

With this configuration, during a printing operation, the piezoelectric actuator 96 is driven depending on printed information to displace the diaphragm 95, thereby changing the volume of the pressure generating chamber 91 rapidly to generate a pressure wave in the pressure generating section 91. The pressure wave causes a part of an ink filled in the pressure generating chamber 91 to be injected to an exterior through the nozzle 94

and ejected as ink droplets 97. The ejected ink droplets 98 arrived in a recording medium such as recording paper to form recording dots. Characters or images are recorded on the recording medium by repeating the formation of recording dots based on printing information.

The ink droplet ejecting operation will be further described. With this on-demand ink jet recording method or system, a single ink droplet is ejected whenever a driving voltage is applied to the piezoelectric actuator 96. In the prior art, however, to eject a single ink droplet, a trapezoidal driving voltage waveform is generally applied to the piezoelectric actuator 96.

The trapezoidal driving voltage waveform comprises a first voltage changing process 51 for linearly increasing a voltage V applied to the piezoelectric actuator 96 from a reference value up to a predetermined value V_1 to compress the pressure generating chamber 91 to eject the ink droplet 97, a voltage maintaining process 52 for maintaining the applied voltage V at the predetermined value V_1 for a certain amount of time (time t_1'), and a second voltage changing process 53 for subsequently returning the applied voltage V_1 to the reference voltage to return the compressed pressure generating chamber 91 to its original state, as shown in Figure 16.

Movement of the piezoelectric actuator caused by an increase or decrease in driving voltage depends on the structure or polarization of the piezoelectric actuator, so some piezoelectric actuators move in a direction opposite to the movement direction of the above-mentioned piezoelectric actuator. Since, however, the reversely operating piezoelectric actuator performs an ejection operation similar to that described above when an opposite driving voltage is applied, a piezoelectric actuator that moves in a direction that compresses the pressure generating chamber when the applied voltage increases, while moving in a direction that inflates the pressure generating chamber when the applied voltage decreases will be described in

the following "BEST MODE FOR CARRYING OUT THE INVENTION" for simple explanation.

In this ink jet recording head, since a single pixel is formed when the ink droplet 97 impacts on recording paper to form a recording dot, if the recording dot has a large diameter, it appears granular to prevent high image quality from being obtained. Thus, a dot size required to obtain a smooth image that does not appear granular (high image quality) is empirically assumed to be 40 μ m or less, and a dot size of 25 μ m or less is considered very preferable. Evidently, the size of the ejected ink droplet 97 may be reduced in order to obtain a small dot size. The relationship between the ink droplet size and the dot size depends on a flying speed (droplet speed) of the ink droplet 97, a physical property of the ink (e.g. viscosity or surface tension), the type of recording paper, or the like, but the dot size is normally about twice as large as the ink droplet size. Consequently, to obtain a dot size of 40 μ m, the ink droplet size must be 20 μ m, and to obtain a smaller size, for example, a dot size of 25 μ m or less, the ink droplet size must be 12.5 μ m or less.

On the other hand, it is theoretically known that if the ink droplet 97 is to be ejected through the nozzle 94 using a pressure wave, the volume q of the ejected ink droplet 97 is proportional to ① the opening area A_n of the nozzle 94, ②the speed (droplet speed) Vd of the ink droplet 97, and ③ the resonance frequency (specific cycle) Tc of the pressure wave in the pressure generating chamber 91 (acoustic fundamental vibration mode) in the as shown in Equation (1). Accordingly, to reduce the size of the ink droplet 97, the nozzle opening diameter, the droplet speed V_d, and the resonance frequency T_c of the pressure wave may be correspondingly reduced.

$$q \propto T_c V_d A_n \qquad \ldots (1)$$

Thus, first, the resonance frequency T_c of the pressure wave will be discussed. The resonance frequency T_c of the pressure wave is reduced by reducing the volume of the pressure generating chamber 91 or increasing

the rigidity of walls of the pressure generating chamber while reducing the acoustic capacity of the pressure generating chamber 91. When, however, the resonance frequency T_c of the pressure wave is extremely reduced, for example, down to the order of several μs, a refilling operation is prevented from being operated smoothly, resulting in adverse effects on ejection efficiency, maximum driving frequency, or the like. Accordingly, the resonance frequency T_c of the pressure wave has a minimum limit between 10 and 20 μ s.

Next, the droplet speed V_d of the ink droplet 97 will be described. The droplet speed V_d affects the impact position accuracy of the ink droplet 97, and a lower droplet speed reduces the impact position accuracy of the ink droplet 97 because the ink droplet 97 is affected by an air flow. Consequently, the droplet speed V_d of the ink droplet 97 cannot be extremely reduced only to reduce the droplet size, and must after all have a fixed value or more (normally about 4 to 10 m/s) in order to obtain high image quality.

Next, the nozzle opening diameter will be described. Due to the above described reasons, it is empirically known that if the resonance frequency T_c of the pressure wave in the pressure generating chamber 91 filled with an ink is set between about 10 and 20 μ s, the droplet speed V_d of the ink droplet 97 is set between about 4 and 10 m/s, and the piezoelectric actuator 96 is driven using the driving voltage waveform shown in Figure 16, then the minimum ink droplet size obtained is equivalent to the nozzle diameter 97. Accordingly, to obtain an ink droplet size of 20 μ m, the nozzle diameter must be 20 μ m, and to obtain an ink droplet size less than 20 μ m, the nozzle diameter must be less than 20 μ m. Forming a nozzle diameter less than 20 μ m, however, makes manufacturing very difficult and increases the likelihood that the nozzle is blocked, thus significantly degrading the reliability and durability of the head. Thus, in fact, a nozzle diameter between 25 and 30 μ m is presently a lower limit, so that under the

above described conditions, the minimum droplet size obtained is between about 25 and 30 μm. It is expected that if the blocking problem is solved in the future, the lower limit of the nozzle diameter will extend to about 20 μm.

As a means for solving these problems, an ink jet driving method has been provided which applies an inversely trapezoidal driving voltage waveform to the piezoelectric actuator 96 to execute "pull and push" to thereby eject ink droplets smaller than the nozzle diameter, as described, for example, in Japanese Patent Laid-Open No. SHO 55-17589.

This driving voltage waveform comprises a first voltage changing process 54 for reducing the voltage V applied to the piezoelectric actuator 96, which is set at a reference voltage V_1 (> 0 V), down to, for example, 0 V in order to inflate the pressure generating chamber 91, a voltage maintaining process 55 for maintaining the reduced applied voltage V at 0 V for a certain amount of time (time t_1'), and a second voltage changing process 56 for subsequently compressing the pressure generating chamber 91 to eject the ink droplet 97, while increasing the voltage V applied to the piezoelectric actuator 96 up to the original voltage V_1 in order to provide for the next ejection, as shown in Figure 17.

When the pressure generating chamber is thus inflated immediately before the ejection, meniscus present at a nozzle opening surface is drawn to an interior of the nozzle, so that the ejection is started in a state where the meniscus has a depressed shape. Accordingly, this method is called "meniscus control", "pull and push" or the like.

According to this "meniscus control (pull and push)" driving method, the meniscus is drawn to the interior of the nozzle immediately before the ejection to reduce the amount of ink inside the nozzle, and ink droplets of a size smaller than the nozzle diameter are formed due to a change in droplet forming conditions before the ejection, thus achieving high quality recording. In addition to this, ejected ink droplets are unlikely to be

affected by wetting of the nozzle opening surface, thereby making the ejection more stable.

In addition, Japanese Patent Laid-Open No. SHO 59-143655 proposes a means for using the meniscus control to modulate the droplet size by varying the amount of meniscus receding immediately before the ejection to eject ink droplets of different sizes through the same nozzle.

Further, several proposals have been made for the waveform of the driving voltage used for the meniscus control. For example, Japanese Patent Laid-Open No. SHO 59-218866 defines a time interval (timing) between the first voltage changing process 54 and the second voltage changing process 56 as a condition for easily obtaining fine droplets. Additionally, Japanese Patent Laid-Open No. HEI 2-192947 discloses a driving method of setting voltage changing times during the first and second voltage changing processes 54 and 56 as integral multiples of the resonance frequency T_c of the pressure wave to prevent the pressure wave from reverberating after the ejection of ink droplets, thereby preventing the occurrence of satellites.

Results of experiments, however, show that even the meniscus controlling (pull and push) driving method (Figure 17) described in the above publication can reduce the ink droplet size to only about 90% of the nozzle diameter, and it is thus practically difficult to obtain fine ink droplets of 20 μm or less to achieve high quality recording. That is, results of ejection experiments conducted by the inventors with a nozzle diameter of 30 μm, a pressure wave resonance frequency T_c of 14 μs, and a droplet speed V_d of 6 m/s and using the driving voltage waveform shown in Figure 17 show that the droplet size obtained (equivalent size calculated from the total amount of ejected ink including satellites) has a lower limit of 28 μm even if the values of the reference voltage V_1, the voltage changing time (falling time) t_1 during the first voltage changing process 54, the voltage maintaining time t_1' during the voltage maintaining process 55, and the

voltage changing time (rising time) t_2 during the second voltage changing process 56 are varied and combined.

Further, if fast driving is executed with the inversely trapezoidal voltage waveform shown in Figure 17, the pressure wave reverberates significantly after the ink ejection, resulting in unstable ejection such as delayed satellites or inappropriate ejection. In the experiments conducted by the inventors, when driving frequency exceeded 8 kHz, bubbles were entrained to the interior of the nozzle or satellite droplets adhered to peripheries of the nozzle, so that a decrease in droplet speed V_d and inappropriate ejection were observed. It has been assured that the head used in the experiments can be driven at 10 kHz or more with the trapezoidal driving voltage waveform shown in Figure 16, so that the inappropriate ejection evidently arises from a reverberated pressure wave, which is caused by the inversely trapezoidal driving voltage waveform.

On the other hand, in the driving voltage waveform shown in Figure 17, if the falling time t_1 and the rising time t_2 are set equal to integral multiples of the resonance frequency T_c, the ejection can be kept stable but it becomes difficult to obtain fine droplets, as described in Japanese Patent Laid-Open No. HEI 2-192947. That is, the results of the experiments conducted by the inventors indicate that if the rising/falling time (t_1/t_2) is made equal to the resonance frequency T_c, the fine droplets obtained have a size of 35 μ m when the nozzle diameter is 30 μ m. Thus, it is difficult to obtain a droplet size equal to or smaller than the nozzle diameter.

The present invention is provided in view of the above described circumstances, and it is an object of the present invention to provide a method for driving an ink jet recording head which method enables fine ink droplets having a smaller size (for example, about 20 μ m) than a nozzle to be stably ejected even at a high frequency.

DISCLOSURE OF THE INVENTION

To attain the above object, the invention set forth in claim 1 provides a method for driving an ink jet recording head which method applies a driving voltage to an electromechanical converter to deform the electromechanical converter to thereby change a pressure in the pressure generating chamber filled with an ink, thus ejecting ink droplets through a nozzle in communication with the pressure generating chamber, the method being characterized in that a voltage waveform of the driving voltage comprises at least a first voltage changing process for applying a voltage in a direction that increases a volume of the pressure generating chamber, a second voltage changing process for then applying a voltage in a direction that reduces the volume of the pressure generating chamber, a third voltage changing process for applying a voltage in a direction that increases the volume of the pressure generating chamber again, and voltage changing times t_2 and t_3 during the second and third voltage changing processes are set to have such lengths as shown below, relative to a resonance frequency T_c of a pressure wave generated in the pressure generating chamber:

$0 < t_2 < T_c/2$

$0 < t_3 < T_c/2$.

The invention set forth in claim 2 is the method for driving an ink jet recording head according to 1, characterized in that a start time of the third voltage changing process is the same as an end time of the second voltage changing process.

The invention set forth in claim 3 is the method for driving an ink jet recording head according to claim 1 or 2, characterized in that the voltage waveform of the driving voltage includes a fourth voltage changing process for applying a voltage in a direction that reduces the voltage of the pressure generating chamber, after the first voltage changing process, the second voltage changing process, and the third voltage changing process.

The invention set forth in claim 4 is the method for driving an ink jet recording head according to claim 3, characterized in that a voltage

changing time t_4 during the fourth voltage changing process is set as follows relative to the resonance frequency T_c of the pressure wave generated in the pressure generating chamber:

$0 < t_4 < T_c/2$.

The invention set forth in claim 5 is the method for driving an ink jet recording head according to claim 3 or 4, characterized in that a time interval between a start time of the second voltage changing process and a start time of the fourth voltage changing process is set substantially half the length of the resonance frequency T_c of the pressure wave generated in the pressure generating chamber.

The invention set forth in claim 6 is the method for driving an ink jet recording head according to any of claims 1 to 5, characterized in that the electomechanical converter is a piezoelectric actuator.

The invention set forth in claim 7 is the method for driving an ink jet recording head according to any of claims 1 to 5, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

THEORETICAL VALIDITY OF THE INVENTION

A theoretical ground for the validity of the present invention will be explained with reference to a lumped-parameter equivalent circuit model.

Figure 12(a) is an equivalent electrical circuit diagram showing that the ink jet recording head shown in Figure 1 is filled with an ink. In Figure 12(a), reference m_0 denotes the inertance (acoustic mass) [kg/m^4] of a vibration system comprising a piezoelectric actuator 4 and a diaphragm 3, reference m_2 denotes the inertance of an ink supply hole 6, reference m_3 denotes the inertance of a nozzle 7, reference r_2 denotes an acoustic resistance [Ns/m^5] from the ink supply hole 6, reference r_3 denotes an acoustic resistance from the nozzle 7, reference c_0 denotes the acoustic capacity [m^5/N] of the vibration system, reference c_1 denotes the acoustic

capacity of the pressure generating chamber 2, reference c_2 denotes the acoustic capacity of the ink supply hole 6, reference c_3 denotes the acoustic capacity of the nozzle 7, and reference φ denotes a pressure [Pa] effected on the ink.

In this case, if the piezoelectric actuator 4 comprises a rigid laminated piezoelectric actuator, the inertance m_0 and acoustic capacity C_0 of the vibration system are negligible. Accordingly, the equivalent circuit in Figure 12(a) is approximately represented by the equivalent circuit in Figure 12(b).

Additionally, if it is assumed that the relation expression $m_2 = km_3$ is established between the inertances m_2 and m_3 of the ink supply hole 6 and the nozzle 7 and that the relation expression $r_2 = kr_3$ is established between the acoustic resistances r_2 and r_3 from the ink supply hole 6 and the nozzle 7 and if circuit analysis is carried out for a case where a driving voltage waveform having a rising angle θ is input as shown in Figure 13(a), then a volume velocity u_3' [m^3/s] in the nozzle section 7 during a rising time $0 \leq t \leq t_1$ is given by Equation (2).

$$u'_3(t,\theta) = \frac{c_1 \tan\theta}{(1+\frac{1}{k})}\left[1 - \frac{w}{E_c}\exp(-D_c \cdot t)\sin(E_c \cdot t - \phi_0)\right] \quad \text{... (2)}$$

$$(0 \leq t \leq t_1)$$

Here is,

$$E_c = \sqrt{\frac{1+\frac{1}{k}}{c_1 m_3} - D^2{}_c}$$

$$D_c = \frac{r_3}{2m_3}$$

$$w^2 = \frac{1+\frac{1}{k}}{c_1 m_3}$$

$$\phi_0 = \tan^{-1}\frac{E_c}{D_c}$$

Next, the volume velocity obtained using a driving voltage waveform of a complicated shape (trapezoid) as shown in Figure 13(b) can be determined by superposing together pressure waves generated at nodes (points A, B, C, and D) of the driving voltage waveform. That is, the volume velocity u_3 [m^3/s] in the nozzle section 7 as occurring in the driving voltage waveform in Figure 13(b) is given by Equation (3).

$$\left.\begin{array}{ll}
u_3(t) = u'_3(t,\theta_1) & (0 \le t \le t_1) \\
u_3(t) = u_3'(t,\theta_1) + u'_3(t-t_1,\theta_2) & (t_1 \le t \le t_1 + t'_1) \\
u_3(t) = u'_3(t,\theta_1) + u'_3(t-t_1,\theta_2) & \\
\quad + u'_3(t-(t_1+t'_1),\theta_3) & (t_1 + t'_1 \le t \le t'_1 + t_2) \\
u_3(t) = u'_3(t,\theta_1) + u'_3(t-t_1,\theta_2) & \\
\quad + u'_3(t-(t_1+t'_1),\theta_3) & \\
\quad + u'_3(t-(t_1+t'_1+t_2),\theta_4) & (t \ge t_1 + t'_1 + t_2)
\end{array}\right\} \quad \ldots (3)$$

When the volume velocity u_3 is actually determined for the driving voltage waveform in Figure 13(a) using Equation (3), the result indicates that temporal variations in volume velocity u_3 vary significantly depending on the rising time t_1. Figure 14 shows an example. In an area corresponding to $t_1 < T_c$ (T_c: resonance frequency of pressure waves), the

volume velocity u_3 becomes zero earlier (the time (t”)) as the rising time t_1 decreases (a) → (b) → (c) in Figure 14.

The particle velocity in the figure is defined as a value obtained by dividing the volume velocity u_3’ of the nozzle section 7 by the opening area of the nozzle. Thus, since the driving voltage waveform significantly varies the waveform of the volume velocity of the nozzle section 7, this can be used as a principle of fine-droplet ejection. This is because the volume q of ejected droplets is substantially proportional to the shaded area in Figure 14, as is apparent from what is expressed by Equation (4).

$$q \propto \int_{t'}^{t''} u(t)dt \qquad \ldots (4)$$

That is, setting a small rising time t_1 reduces the area of the shaded portion, thereby obtaining a small volume of droplets (droplet size) q. In particular, fine droplets can be ejected by setting the rising time t_1 equal to or shorter than half of the resonance frequency T_c of the pressure wave (this also applies to the falling time t_2).

If the driving voltage waveform shown in Figure 17 is used to execute meniscus control (pull and push), it is particularly desirable for fine-droplet ejection to set the rising time t_2 equal to or shorter than half of the resonance frequency T_c of the pressure wave. This is because ink droplets can be made further smaller due to the droplet size reducing effect based on the conventional meniscus control as well as the above-described variation of the volume velocity waveform (a decrease in shaded area).

However, it is very difficult to obtain fine droplets of 20 μm size simply by setting a shorter rising time t_2 for the inversely trapezoidal driving voltage waveform shown in Figure 17. Thus, if the piezoelectric actuator 4 is imparted with a third voltage changing process (voltage lowering process) for rapidly increasing the volume of the pressure generating chamber 2 immediately after the driving voltage waveform has

risen, as shown in Figure 4(a), then the shaded area further decreases to enable the ink droplets to be made further smaller, as shown in Figure 5(a). Additionally, the effect of the falling edge on the reduction of the droplet size depends on the time interval between the rising and falling edges; if the falling edge is set to appear immediately after the rising edge, that is, the start time of the third voltage changing process is set equal to the end time of the second voltage changing process, as shown in Figure 4(b), the smallest droplet diameter is obtained as shown in Figure 5(b).

Further, as described above, the use of a driving voltage waveform having a rapid rising or falling edge causes the pressure wave to reverberate significantly after the ejection, so that a problem such as generation of satellites or a reduced stability of fast driving is likely to occur. Thus, according to the inventions set forth in claims 3, 4, and 5, a fourth voltage changing process (voltage raising process) for generating pressure waves to restrain reverberation is provided after the third voltage changing process. This serves to compensate for previously generated pressure waves to prevent reverberation, while improving the ejection stability.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1(a) is a sectional view of an ink jet recording head mounted in an ink jet recording apparatus as a first embodiment of the present invention. Figure 1(b) is an exploded sectional view showing the ink jet recording head as disassembled;

Figure 2 is a block diagram showing the electrical configuration of a droplet size non-modulated driving circuit for driving the ink jet recording head;

Figure 3 is a block diagram showing the electrical configuration of the droplet size modulated driving circuit for driving the ink jet recording head;

Figure 4 is a waveform diagram showing the configuration of driving voltage waveforms used in a method for driving the ink jet recording head;

Figure 5 is a waveform diagram showing waveforms of the volume velocity of an ink as occurring in a nozzle section due to the driving voltage waveform;

Figure 6 is a view useful in explaining the effects of this embodiment;

Figure 7 is a view useful in explaining the effects of this embodiment;

Figure 8 is a view useful in explaining the effects of this embodiment;

Figure 9 is a waveform diagram showing the configuration of driving voltage waveforms used in a method for driving the ink jet recording head as a second embodiment of the present invention;

Figure 10 is a view useful in explaining the effects of this embodiment;

Figure 11 is a view useful in explaining the effects of this embodiment, showing how ejection varies depending on whether or not reverberation is restrained;

Figure 12 is a view showing a diagram of an equivalent electric circuit in which an ink jet recording head applied to the present invention is filled with an ink;

Figure 13 is a waveform diagram useful in explaining a method for driving the ink jet recording head;

Figure 14 is a waveform diagram useful in explaining the method for driving the ink jet recording head;

Figure 15 is a sectional view useful in explaining a conventional technique, schematically showing the basic configuration of an ink jet recording head called a “Kyser type” and belonging to on-demand ink jet recording heads;

Figure 16 is a waveform diagram showing the configuration of driving voltage waveforms used in a conventional method for driving a ink jet recording head; and

Figure 17 is a waveform diagram showing the configuration of driving voltage waveforms used in another conventional method for driving a ink jet recording head.

BEST MODE FOR CARRYING OUT THE INVENTION

The best mode for carrying out the present invention will be described below with reference to the drawings. A specific description will be given using embodiments.

First embodiment

Figure 1(a) is a sectional view showing the configuration of an ink jet recording head mounted in an ink jet recording apparatus as a first embodiment of the present invention. Figure 1(b) is an exploded sectional view showing the ink jet recording head as disassembled. Figure 2 is a block diagram showing the electrical configuration of a droplet size non-modulated driving circuit for driving the ink jet recording head. Figure 3 is a block diagram showing the electrical configuration of the droplet size modulated driving circuit for driving the ink jet recording head. Figure 4 is a waveform diagram showing the configuration of driving voltage waveforms used in a method for driving the ink jet recording head. Figure 5 is a waveform diagram (already described) showing waveforms of the volume velocity of an ink as occurring in a nozzle section due to the driving voltage waveform. Figures 6 and 7 are views useful in explaining the effects of this embodiment.

The ink jet recording head in this example relates to a on-demand Kyser type multinozzle recording head for ejecting ink droplets 1 as required to print characters or images on recording paper as shown in Figure 1(a), and as shown in Figure 1, comprises a plurality of pressure generating chambers 2 each formed into an elongated cubic and arranged in a direction perpendicular to the sheet of the drawing, a diaphragm 3 constituting a

bottom surface of each of the pressure generating chambers 2, which is located at the bottom of Figure 1, a plurality of piezoelectric actuators 4 arranged in parallel on a rear surface of the diaphragm correspondingly to the pressure generating chambers 2 and composed of laminated piezoelectric ceramics, a common ink chamber (ink pool) 5 linked to an ink tank (not illustrated) to supply an ink to each of the pressure generating chambers 2, a plurality of ink supply holes (communication holes) 6 for allowing the common ink chamber 5 to communicate with each pressure generating chamber 2 on a one-to-one correspondence, and a plurality of nozzles 7 formed so as to correspond to the different pressure generating chambers 2 and ejecting the ink droplets 1 from an angled tip portion projecting upward from each pressure generating chamber 2 as shown in Figure 1. In this case, the common ink chamber 5, the ink supply passages 6, the pressure generating chambers 2, and the nozzles 7 form a channel system through which the ink moves in this order, the piezoelectric actuator 4 and the diaphragm 3 constitute a vibration system for applying pressure waves to the ink in the pressure generating chambers 2, and contacts between the channel system and the vibration system constitute the bottom surface of the pressure generating chambers 2 (that is, a top surface of the diaphragm 3, which is located closer to the bottom of the figure).

In a process of manufacturing a head according to this embodiment, the following components are provided beforehand: a nozzle plate 7a having the plurality of nozzles 7 formed by drilling the nozzle plate by means of precision pressing and arranged in rows or in a staggered manner, in a (super-) periodic or in having any periodical shift, a pool plate 5a having a space portion formed for the common ink chamber 5, a supply hole plate 6a having the ink supply holes 6 drilled therein, a pressure generating chamber plate 2a having space portions for the plurality of pressure generating chambers 2, and a vibration plate 3a constituting the plurality of diaphragms 3, as shown in Figure 1(b). These plates 2a, 3a, and 5a to 7a are bonded

and joined together using an epoxy-based adhesive layer of 20 μm thickness (not illustrated) to thereby produce a laminated plate. Then, the produced laminated plate and the piezoelectric actuators 4 are joined together using an epoxy-based adhesive layer to thereby manufacture an ink jet recording head of the above configuration. In this example, the vibration plate 3a comprises a nickel plate of 50 to 75 μm molded by means of electroforming, while the other plates 2a and 5a to 7a each comprise a stainless plate of 50 to 75 μm. The nozzles 7 in this example each have an opening diameter of about 30 μm, a bottom diameter of about 65 μm, and a length of about 75 μm and are each tapered in a manner such that its diameter increases toward the pressure generating chamber 2. The ink supply holes 6 are also each formed to have the same shape as the nozzle 7.

Next, the electrical configuration of a drive circuit for driving the ink jet recording head of this example configured as stated above will be described with reference to Figures 2 and 3.

The ink jet recording apparatus of this example has a CPU (Central Processing Unit) (not illustrated), a ROM, a RAM, and the like. The CPU executes programs stored in the ROM and uses various registers and flags stored in the RAM to control each section of the apparatus so as to print characters or images on recording paper based on print information supplied from a higher apparatus such as a personal computer via an interface.

First, the driving circuit in Figure 2 generates a driving voltage waveform signal corresponding to Figure 4(a), amplify the power of this signal, and then supplies the amplified signal to the predetermined piezoelectric actuators 4, 4, ... corresponding to print information to drive them to eject the ink droplets 1 always having substantially the same size, thereby printing characters or images on recording paper. The driving circuit substantially comprises a waveform generating circuit 21, a power amplifying circuit 22, and a plurality of switching circuits 23, 23, ...

connected to the piezoelectric actuators 4, 4, ... on a one-to-one correspondence.

The waveform generating circuit 21 comprises a digital analog conversion circuit and an integration circuit to convert driving voltage waveform data read out from a predetermined storage area of the ROM, into analog data, and then integrates the latter to generate a driving voltage waveform signal corresponding to Figure 4(a). The power amplifying circuit 22 amplifies the power of the driving voltage waveform signal supplied by the waveform generating circuit 21 to output an amplified driving voltage waveform signal, shown in Figure 4(a). The switching circuit 23 has its input end connected to an output end of the power amplifying circuit 22 and its output end connected to one end of the corresponding piezoelectric actuator 4. When a control signal corresponding to print information output from a drive controlling circuit (not illustrated) is input to a control end of the switching circuit 23, the latter is switched on to apply the amplified driving voltage waveform signal (Figure 4(a)) output from the corresponding power amplifying circuit 22, to the piezoelectric actuator 4. Then, the piezoelectric actuator 4 displaces the diaphragm 3 depending on the applied amplified driving voltage waveform signal, to change the volume of the pressure generating chambers 2. Consequently, a predetermined pressure wave is generated in the pressure generating chambers 2 filled with an ink, thereby ejecting the ink droplets 1 of a predetermined size through the nozzles 7. In the recording head of this embodiment, the pressure wave in the pressure generating chambers 2 filled with the ink has a resonance frequency T_c of 14 μ s. The ejected ink droplets impact on recording medium such as recording paper to form recording dots. The formation of recording dots is then repeated based on the print information to record characters or images on the recording paper in a binary form.

Next, the driving circuit in Figure 3 is of what is called a droplet size modulated type which switches the size of the ink droplets ejected through the nozzle, between multiple levels (in this example, three levels including large droplets of 40 μ m size, medium droplets of 30 μ m size, and small droplets of 20 μ m size) to print characters or images on the recording paper with multiple gradations. The driving circuit substantially comprises three types of waveform generating circuits 31a, 31b and 31c corresponding to the droplet sizes, power amplifying circuits 32a, 32b, and 32c connected to these waveform generating circuits 31a, 31b, and 31c on a one-to-one correspondence, and a plurality of switching circuits 33, 33, ... connected to the piezoelectric actuators 4, 4, ... on a one-to-one correspondence.

The waveform generating circuits 31a to 31c each comprise a digital analog conversion circuit and an integration circuit, and one 31a of these waveform generating circuits 31a to 31c converts driving voltage waveform data for large-droplet ejection into analog data, the signal being read out by the CPU from a predetermined storage area of the ROM, and then integrates this signal to generate a driving voltage waveform signal for large-droplet ejection. The waveform generating circuit 31b converts driving voltage waveform data for medium-droplet ejection into analog data, the signal being read out by the CPU from a predetermined storage area of the ROM, and then integrates this signal to generate a driving voltage waveform signal for medium-droplet ejection. Additionally, the waveform generating circuit 31c converts driving voltage waveform data for small-droplet ejection into analog data, the signal being read out by the CPU from a predetermined storage area of the ROM, and then integrates this signal to generate a driving voltage waveform signal for small-droplet ejection corresponding to Figure 4(a). The power amplifying circuit 32a amplifies the power of the driving voltage waveform signal for large-droplet ejection supplied by the waveform generating circuit 31a to output an amplified driving waveform signal for large-droplet ejection. The power amplifying

circuit 32b amplifies the power of the driving voltage waveform signal for medium-droplet ejection supplied by the waveform generating circuit 31b to output an amplified driving voltage waveform signal for medium-droplet ejection.

The power amplifying circuit 32c amplifies the power of the driving voltage waveform signal for small-droplet ejection supplied by the waveform generating circuit 31c to output an amplified driving voltage waveform signal for small-droplet ejection (Figure 4(a)).

Further, the switching circuit 33 comprises a first, a second, and a third transfer gates (not illustrated). The first transfer gate has its input end connected to the output end of the power amplifying circuit 32a, the second transfer gate has its input end connected to the output end of the power amplifying circuit 32b, and the third transfer gate has its input end connected to the output end of the power amplifying circuit 32c. The first, second, and third transfer gates have their output ends connected to one end of the corresponding common piezoelectric actuator 4. When a gradation controlling signal corresponding to print information output from a drive controlling circuit (not illustrated) is input to a control end of the first transfer gate, the latter is turned on to apply to the piezoelectric actuator 4 the amplified driving voltage waveform signal for large-droplet ejection output from the power amplifying circuit 32a.

At this time, the piezoelectric actuator 4 displaces the diaphragm 3 depending on the applied amplified driving voltage waveform signal to rapidly change (increase or reduce) the volume of the pressure generating chamber 2 to thereby generate a predetermined pressure wave in the pressure generating chamber 2 filled with the ink, thus ejecting the large ink droplets 1 through the nozzle 7. When a gradation controlling signal corresponding to print information output from the drive controlling circuit is input to a control end of the second transfer gate, the latter is turned on to apply to the piezoelectric actuator 4 the amplified driving voltage waveform

signal for medium-droplet ejection output from the power amplifying circuit 32b. At this time, the piezoelectric actuator 4 displaces the diaphragm 3 depending on the applied amplified driving voltage waveform signal to rapidly change (increase or reduce) the volume of the pressure generating chamber 2 to thereby generate a predetermined pressure wave in the pressure generating chamber 2 filled with the ink, thus ejecting the medium ink droplets 1 through the nozzle 7. When a gradation controlling signal corresponding to print information output from the drive controlling circuit is input to a control end of the third transfer gate, the latter is turned on to apply to the piezoelectric actuator 4 the amplified driving voltage waveform signal for small-droplet ejection output from the power amplifying circuit 32c (Figure 4(a)). At this time, the piezoelectric actuator 4 displaces the diaphragm 3 depending on the applied amplified driving voltage waveform signal to rapidly change (increase or reduce) the volume of the pressure generating chamber 2 to thereby generate a predetermined pressure wave in the pressure generating chamber 2 filled with the ink, thus ejecting the small ink droplets 1 through the nozzle 7. The ejected ink droplets impact on the recording medium such as recording paper to form recording dots. The formation of such recording dots is repeated based on print information to record characters or images on recording paper.

In this embodiment, an ink jet recording apparatus exclusively used for binary recording incorporates the driving circuit in Figure 2, and an ink jet recording apparatus also used for gradation recording incorporates the driving circuit in Figure 3.

The above-mentioned amplified driving voltage waveform signal comprises a first voltage changing process 41 for lowering a voltage V applied to the piezoelectric actuator 4 ($V_1 \rightarrow 0$) to inflate the pressure generating chamber 2 to thereby cause meniscus to recede, a first voltage retaining process 42 for retaining the lowered applied voltage V for a certain period of time (time t_1') ($0 \rightarrow 0$), a second voltage changing process

43 for raising the voltage ($0 \rightarrow V_2$) to compress the pressure generating chamber 2 to eject the ink droplets 1, a second voltage retaining process 44 for retaining the raised applied voltage V for a certain period of time (time t_2') ($V_2 \rightarrow V_2$), and a third voltage changing process 45 for lowering the voltage ($V_2 \rightarrow 0$) to inflate the pressure generating chamber 2 again. The voltage changing times t_2 and t_3 during the second and third voltage changing processes 43 and 45 are set to have such lengths as shown below, relative to the resonance frequency T_c of the pressure wave generated in the pressure generating chamber 2.

$0 < t_2 < T_c/2$

$0 < t_3 < T_c/2$

Next, ejection experiments were conducted for the ink jet driving method of this example under the following driving voltage waveform conditions:

reference voltage $V_1 = 10$ V

voltage changing time $t_1 = 3\,\mu$s during the first voltage changing process 41

voltage retaining time $t_1' = 4\,\mu$s during the first voltage retaining process 42

voltage changing time $t_2 = 2\,\mu$s during the second voltage changing process 43

voltage changing time $t_3 = 2\,\mu$s during the third voltage changing process 45

The voltage retaining time t_2' during the second voltage retaining process 44 was varied and resulting variations in droplet diameter were recorded. The voltage change amount V_2 during ejection, that is, during the second voltage changing process 43 was adjusted such that a droplet speed was always 6 m/s. Figure 6 is a characteristic diagram showing the relationship between the voltage retaining time t_2' during the second voltage retaining process 44 and the ink droplet size. In this diagram, the solid line shows measured

values obtained under the above-mentioned conditions, and the broken line shows converted values of the droplet size obtained by calculating a volume speed u_3 in the nozzle portion 7, substituting the result of the calculation for Equation (4) to calculate the droplet volume q, and determining a droplet size from the calculated droplet volume q. As seen in Figure 6, the theoretical values agree well with the experimental values despite a small difference in absolute value.

As seen in Figure 6, the addition of the third voltage changing process 45 enables the ink droplets to be made significantly small. In particular, it has been assured that if an end time of the second voltage changing process 43 is the same as a start time of the third voltage changing process 45, that is, the voltage retaining time t_2' during the second voltage retaining process 44 is set at 0 μ s, as shown in Figure 4(b), ink droplets of the smallest diameter (19 μ m) are obtained to enable fine droplets in the order of 20 μ m to be ejected.

Then, with the voltage retaining time t_2' during the second voltage retaining process 44 set at 0 μs, the voltage changing time (rising time t_2) during the second voltage changing process 43 and the voltage changing time (falling time t_3) during the third voltage changing process 45 were varied, and variations in ink droplet diameter were measured. Figure 7 is a graph showing the relationship between the falling time t_2/rising time t_3 and the ink droplet size. Figure 7 shows that fine ink droplets are effectively ejected by setting the falling time t_2/rising time t_3 equal to or shorter than half of the resonance frequency T_c of the pressure wave.

The size of ejected ink droplets depends on the resonance frequency T_c of the pressure wave or the nozzle diameter as is apparent from Equation (1), and fine droplets in the order of 20 μm are not necessarily obtained even by setting the rising time t_2/falling time t_3 during the second voltage changing process 43/third voltage changing process 45 equal to or shorter than half of the resonance frequency T_c. That is, setting the rising time

t_2/falling time t_3 equal to or shorter than half of the resonance frequency T_c is not a sufficient but a necessary condition.

Next, for comparison with the prior art, ejection experiments were conducted using the conventional driving voltage waveform in Figure 17. That is, the following conditions were set:

reference voltage $V_1 = 10$ V

voltage changing time $t_1 = 3\,\mu$s during a first voltage changing process 54

voltage retaining time $t_1' = 4\,\mu$s during a first voltage retaining process 5

A rising time t_3 during ejection, that is during a second voltage changing process 56 was varied and resulting variations in droplet diameter were recorded. The voltage change amount V_2 during ejection was adjusted such that the droplet speed was always 6 m/s.

Figure 8 is a characteristic diagram showing the relationship between a rising time t_2 during the second voltage retaining process 56 and the ink droplet size. In this diagram, the solid line shows measured values obtained under the above-mentioned conditions, and the broken line shows converted values of the droplet size obtained based on Equations (3) and (4). As seen in Figure 8, the theoretical values agree well with the experimental values despite a small difference in absolute value.

As is apparent from Figure 8, the droplet size decreases linearly with the rising time t_3 within the range of $t_3 < T_c$ (T_c: resonance frequency of the pressure wave). Accordingly, if a conventional "meniscus control (pull and push)" waveform such as that shown in Figure 17 is used, it is also advantageous to set the rising time t_3 as short as possible. However, even if the rising time t_3 can be set at $0\,\mu$s, a droplet size of about $28\,\mu$m is predicted from Figure 8 and it is difficult to obtain fine droplets in the order of $20\,\mu$m.

Second Embodiment

Figure 9 is a waveform diagram showing the configuration of a driving voltage waveform used for a method for driving an ink jet recording head as a second embodiment of the present invention.

In this second embodiment, the amplified driving voltage waveform signal comprises a first voltage changing process 91 for lowering a voltage V applied to the piezoelectric actuator 4 ($V_1 \rightarrow 0$) to inflate the pressure generating chamber 2 to thereby cause meniscus to recede, a first voltage retaining process 92 for retaining the lowered applied voltage V for a certain period of time (time t_1') ($0 \rightarrow 0$), a second voltage changing process 93 for raising the voltage ($0 \rightarrow V_2$) to compress the pressure generating chamber 2 to eject the ink droplets 1, a second voltage retaining process 94 for retaining the raised applied voltage V for a certain period of time (time t_2') ($V_2 \rightarrow V_2$), a third voltage changing process 95 for lowering the voltage ($V_2 \rightarrow 0$) to inflate the pressure generating chamber 2 again, a third voltage retaining process 96 for retaining the lowered applied voltage V for a certain period of time (time t_3') ($0 \rightarrow 0$), and a fourth voltage changing process 97 for raising the voltage ($0 \rightarrow V_1$) to generate a pressure wave for restraining reverberation. The voltage changing times t_2 and t_3 during the second and third voltage changing processes 93 and 95 are set to have such lengths as shown below, relative to the resonance frequency T_c of the pressure wave generated in the pressure generating chamber 2.

$0 < t_2 < T_c/2$

$0 < t_3 < T_c/2$

In this connection, to efficiently prevent the pressure wave from reverberating, it is preferable to set a voltage changing time t_4 during the fourth voltage changing process 97 to have such a length as shown below, relative to the resonance frequency T_c of the pressure wave generated in the pressure generating chamber 2.

$0 < t_4 < T_c/2$

That is, this configuration is substantially similar to that of the first embodiment except that the fourth voltage changing process 97 and the accompanying third voltage retaining process 96 are provided.

Next, ejection experiments were conducted for the ink jet driving method of the second embodiment under the following driving voltage waveform conditions:

reference voltage $V_1 = 10$ V

voltage change amount $V_2 = 8$V during ejection, that is, during the second voltage changing process 93

voltage changing time $t_1 = 3\,\mu$s during the first voltage changing process 91

voltage retaining time $t_1' = 4\,\mu$s during the first voltage retaining process 92

voltage changing time $t_2 = 2\,\mu$s during the second voltage changing process 93

voltage retaining time $t_2' = 0\,\mu$s during the second voltage retaining process 94

voltage changing time $t_3 = 2\,\mu$s during the third voltage changing process 95

voltage retaining time $t_3' = 2\,\mu$s during the third voltage retaining process 96

voltage changing time $t_4 = 3\,\mu$s during the fourth voltage changing process 97

Then, variations in ink volume velocity occurring in the nozzle portion 7 when the apparatus is driven with the driving voltage waveform in Figure 9 under the above voltage conditions were calculated using Equations (3) and (4). The results of the calculation are shown in Figure 10(b) as particle velocity.

Next, for comparison with the first embodiment, ejection experiments were conducted using the conventional driving voltage waveform in Figure 4. That is, the following conditions were set:

reference voltage $V_1 = 10$ V

voltage change amount $V_2 = 8$V during ejection, that is, during the second voltage changing process 93

voltage changing time $t_1 = 3\,\mu$s during the first voltage changing process 91

voltage retaining time $t_1' = 4\,\mu$s during the first voltage retaining process 92

voltage changing time $t_2 = 2\,\mu$s during the second voltage changing process 93

voltage retaining time $t_2' = 0\,\mu$s during the second voltage retaining process 94

voltage changing time $t_3 = 2\,\mu$s during the third voltage changing process 95

Then, variations in ink volume velocity occurring in the nozzle portion 7 when the apparatus is driven with the driving voltage waveform in Figure 4 under the above voltage conditions were calculated using Equations (3) and (4). The results of the calculation are shown in Figure 10(a) as particle velocity.

If the apparatus is driven with the driving voltage waveform (Figure 4) of the first embodiment, ink droplets smaller than the nozzle diameter can be ejected due to the first to third voltage changing processes 41, 43, and 45, whereas the ejection may be unstable. This is because if the apparatus is driven with the driving voltage waveform (Figure 4) of the first embodiment, the pressure wave reverberates significantly even after the ejection, in other words, even after the first wave associated with the ejection of ink droplets, thereby making the ejection unstable, as seen in Figure 10(a). The results of the experiments conducted by the inventors

show that such significant pressure wave reverberation is likely to make generation of satellites unstable and to cause inappropriate ejection particularly at a high driving frequency.

In contrast, if the apparatus is driven with the driving voltage waveform (Figure 9) of the second embodiment, since the fourth voltage changing process 97 is executed after the first to third voltage changing processes 91, 93, and 95, a pressure wave occurs which compensates for the occurring pressure wave reverberation, thereby significantly attenuating the amplitude of the volume velocity after the first wave as seen in Figure 10(b). Consequently, the pressure wave is effectively prevented from reverberating after the ejection. Therefore, fine droplets can be stably ejected even at a high driving frequency according to the driving method of the second embodiment.

Figure 11 shows photographs showing how the ejection varies depending on whether or not the reverberation is restrained.

As is apparent from the photographs in Figure 11, it has been assured that in the first embodiment (reverberation is not restrained), tails of ink droplets are bent at a driving frequency of 8 kHz or more and satellites fly unstably (Photo (a)), whereas in the second embodiment (reverberation is restrained), the ejection does not substantially vary even at 10 kHz (Photo (b)).

In the second embodiment, to efficiently restrain it is desirable to set the voltage changing time t_4 during the fourth voltage changing process 97 equal to or shorter than half of the resonance frequency T_c of the pressure wave. Additionally, the pressure wave is most efficiently restrained from reverberating by setting the time interval $(t_2 + t_2' + t_3 + t_3')$ between a start time of the second voltage changing process 93 and a start time of the fourth voltage changing process 97, equal to or shorter than half of the resonance frequency T_c of the pressure wave in the pressure generating chamber 2. This is because the pressure wave having a phase opposite to that of the

pressure wave generated by the second voltage changing process 93 is generated to efficiently cancel the latter pressure wave effectively.

The embodiment of the present invention has been described in detail with reference to the drawings, but the specific configuration is not limited to this embodiment and changes to the design are embraced in the present invention as long as they do not deviate from the spirits thereof. For example, the shape of the nozzles and the ink supply holes is not limited to the taper. Likewise, the shape of the openings is not limited to the circle but may be a rectangle, triangle, or others. In addition, the positional relationship between the nozzle and the pressure generating chamber and the ink supply hole is not limited to the structures shown in the embodiments, but for example, the nozzle may of course be arranged in the center of the pressure generating chamber.

Further, in the above described first embodiment, the voltage (0 V) at the end of the first voltage changing process equals the voltage (0 V) at the end of the third voltage changing process. The present invention, however, is not limited to this, but these voltage may be different. In the above described second embodiment, the voltage changing times t_2, t_3, and t_4 of the second to fourth voltage changing processes 93, 95, and 97 are equal. The present invention, however, is not limited to this, but these voltage changing times may be separately set. In the second embodiment, the voltage at the end of the fourth voltage changing process equals the reference voltage. The present invention, however, is not limited to this, but this voltage may be set at a different value. In the above embodiments, the reference voltage is offset from 0 V. The present invention, however, is not limited to this, and the reference voltage may be set at an arbitrary value.

Additionally, the above described embodiments show the results of the experiments for the recording head having a pressure wave resonance frequency T_c of 14 μs, but it has been confirmed that effects similar to

those described in the above embodiments are obtained with a different resonance frequency T_c. If, however, fine droplets in the order of 20 μ m are to be ejected, the resonance frequency is desirably set at 20 μ s or less.

Further, the above described embodiments use the recording head of 30 μ m diameter, but the present invention is not limited to this. An ink jet recording head including a nozzle having an opening diameter of 20 to 40 μ m can be driven to eject droplets of 5 to 25 μ m size. The practical lower limit of the nozzle diameter is expected to decrease to about 20 μ m if the blocking problem is solved in the future.

Moreover, the above described embodiments use the Kyser ink jet recording head, but the present invention is not limited to this type.

INDUSTRIAL APPLICABILITY

As described above, according to the configuration of the present invention, fine ink droplets of a size smaller than the nozzle diameter can be stably ejected at a high driving frequency. Specifically, fine ink droplets in the order of 20 μ m can be stably ejected at a high frequency even with a nozzle diameter of 30 μ m.

CLAIMS

1. A method for driving an ink jet recording head which method applies a driving voltage to an electromechanical converter to deform the electromechanical converter to thereby change a pressure in the pressure generating chamber filled with ink, thus ejecting ink droplets through a nozzle in communication with the pressure generating chamber, the method being characterized in that:

a voltage waveform of said driving voltage comprises:

at least a first voltage changing process for applying a voltage in a direction that increases a volume of said pressure generating chamber;

a second voltage changing process for then applying a voltage in a direction that reduces the volume of said pressure generating chamber; and

a third voltage changing process for applying a voltage in a direction that increases the volume of said pressure generating chamber again, and

voltage changing times t_2 and t_3 during the second and third voltage changing processes are set to have such lengths as shown below, relative to a resonance frequency T_c of a pressure wave generated in the pressure generating chamber:

$0 < t_2 < T_c/2$

$0 < t_3 < T_c/2$.

2. The method for driving an ink jet recording head according to claim 1, characterized in that a start time of said third voltage changing process is about the same as an end time of said second voltage changing process.

3. The method for driving an ink jet recording head according to claim 1 or 2, characterized in that the voltage waveform of said driving voltage includes a fourth voltage changing process for applying a voltage in

a direction that reduces the voltage of said pressure generating chamber, after said first voltage changing process, said second voltage changing process, and said third voltage changing process.

4. The method for driving an ink jet recording head according to claim 3, characterized in that a voltage changing time t_4 during said fourth voltage changing process is set as follows relative to the resonance frequency T_c of the pressure wave generated in said pressure generating chamber:

$$0 < t_4 < T_c/2$$

5. The method for driving an ink jet recording head according to claim 3 or 4, characterized in that a time interval between a start time of said second voltage changing process and a start time of said fourth voltage changing process is set substantially half the length of the resonance frequency T_c of the pressure wave generated in said pressure generating chamber.

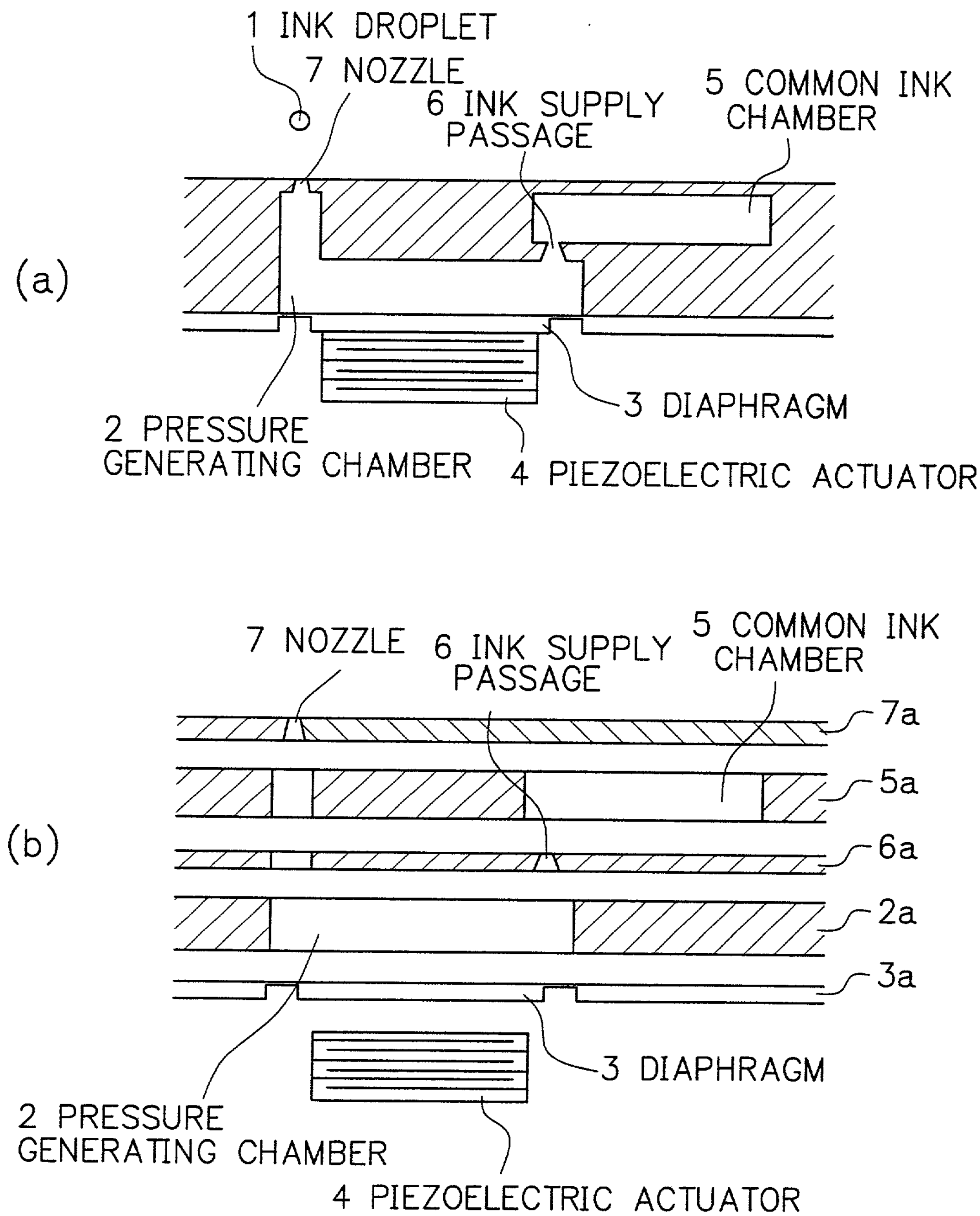
6. The method for driving an ink jet recording head according to any of claims 1 to 5, characterized in that said electomechanical converter is a piezoelectric actuator.

7. The method for driving an ink jet recording head according to any of claims 1 to 5, characterized in that an ink jet recording head with the nozzle of 20 to 40 μ m opening diameter is driven to eject ink droplets of 5 to 25 μ m size.

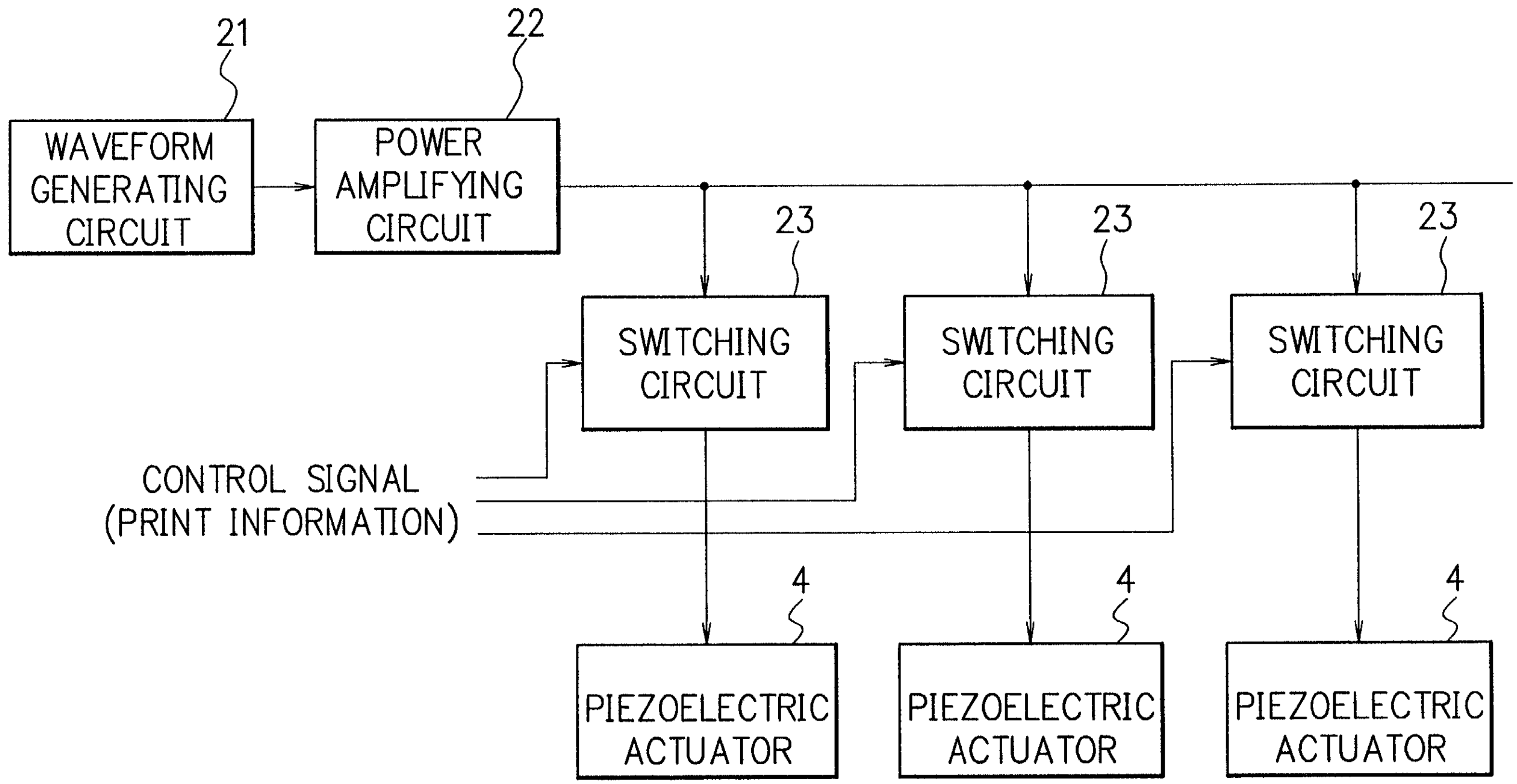
ABSTRACT

To enable fine droplets of a diameter smaller than a nozzle diameter to be stably ejected at a high driving frequency. The present invention relates to a method for driving an ink jet recording head which method applies a driving voltage to a piezoelectric actuator 4 to change a pressure in a pressure generating chamber 2, thus ejecting ink droplets 1 through a nozzle 7 in communication with the pressure generating chamber 2. A waveform of the driving voltage comprises a first voltage changing process for applying a voltage in a direction that inflates the pressure generating chamber 2, a second voltage changing process for then applying a voltage in a direction that compresses the volume of the pressure generating chamber, a third voltage changing process for applying a voltage in a direction that inflates the volume of the pressure generating chamber 2 again, and voltage changing times t_2 and t_3 during the second and third voltage changing processes are set to have such lengths as shown below, relative to a resonance frequency T_c of a pressure wave generated in the pressure generating chamber 2: $0 < t_2 < T_c/2$ and $0 < t_3 < T_c/2$.

F I G. 1

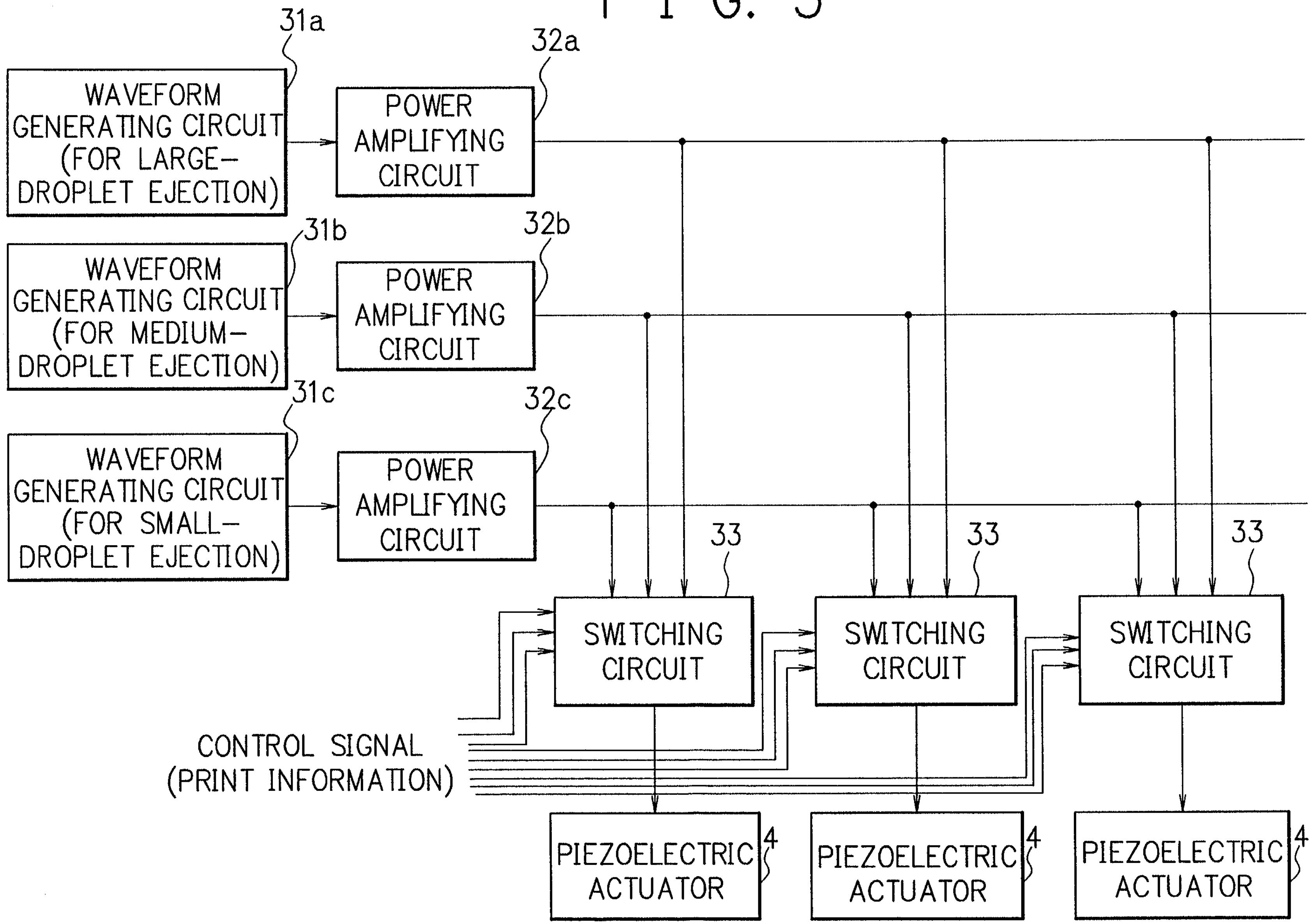

(a)
1 INK DROPLET
7 NOZZLE
6 INK SUPPLY PASSAGE
5 COMMON INK CHAMBER
3 DIAPHRAGM
2 PRESSURE GENERATING CHAMBER
4 PIEZOELECTRIC ACTUATOR
(b)
7 NOZZLE
6 INK SUPPLY PASSAGE
5 COMMON INK CHAMBER
7a
5a
6a
2a
3a
3 DIAPHRAGM
2 PRESSURE GENERATING CHAMBER
4 PIEZOELECTRIC ACTUATOR

F I G. 2

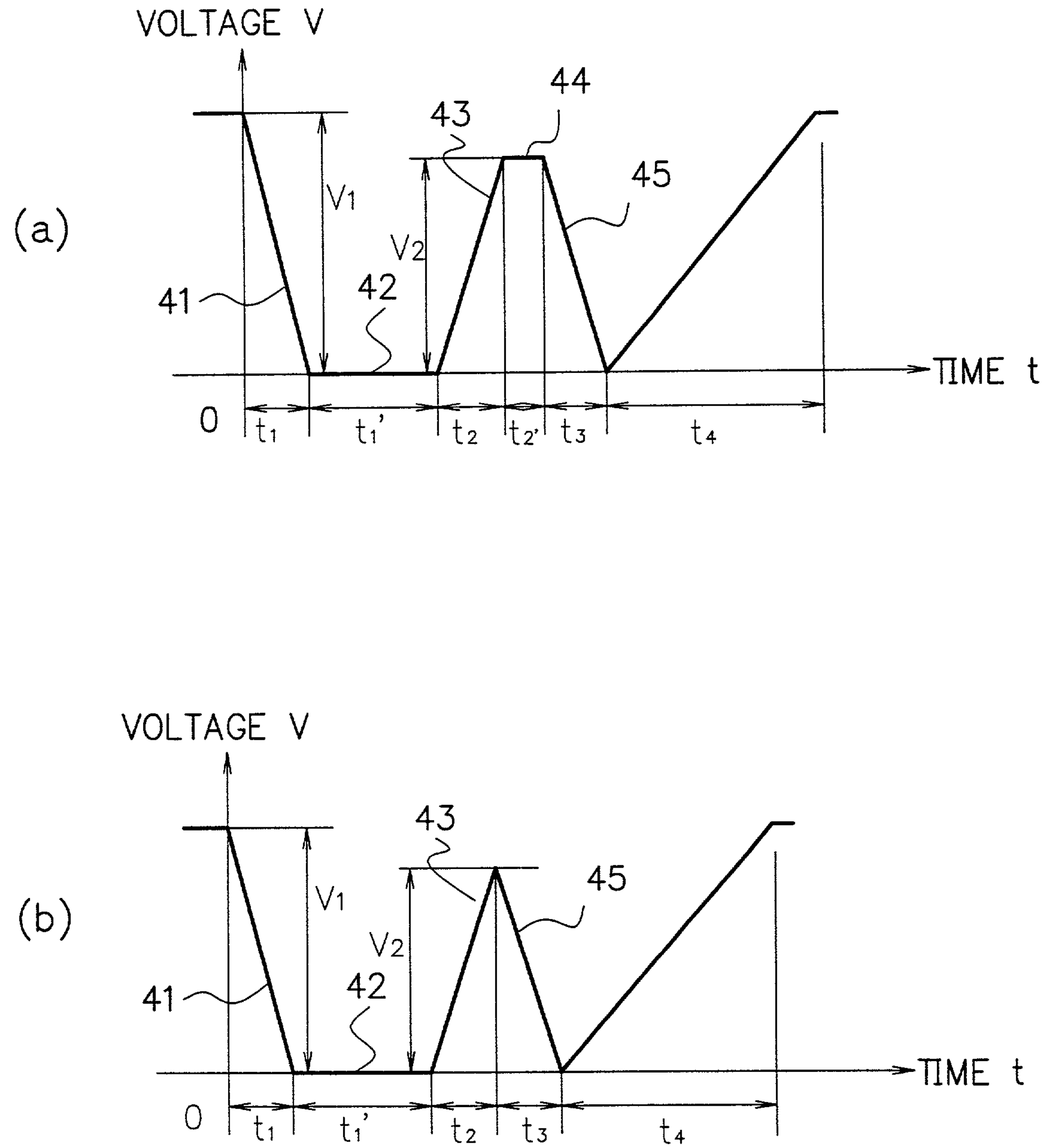


21
WAVEFORM GENERATING CIRCUIT
22
POWER AMPLIFYING CIRCUIT
23
SWITCHING CIRCUIT
23
SWITCHING CIRCUIT
23
SWITCHING CIRCUIT
CONTROL SIGNAL (PRINT INFORMATION)
4
PIEZOELECTRIC ACTUATOR
4
PIEZOELECTRIC ACTUATOR
4
PIEZOELECTRIC ACTUATOR

F I G. 3


31a
WAVEFORM GENERATING CIRCUIT (FOR LARGE-DROPLET EJECTION)
31b
WAVEFORM GENERATING CIRCUIT (FOR MEDIUM-DROPLET EJECTION)
31c
WAVEFORM GENERATING CIRCUIT (FOR SMALL-DROPLET EJECTION)
32a
32b
32c
POWER AMPLIFYING CIRCUIT
POWER AMPLIFYING CIRCUIT
POWER AMPLIFYING CIRCUIT
33
33
33
SWITCHING CIRCUIT
SWITCHING CIRCUIT
SWITCHING CIRCUIT
CONTROL SIGNAL (PRINT INFORMATION)
4
4
4
PIEZOELECTRIC ACTUATOR
PIEZOELECTRIC ACTUATOR
PIEZOELECTRIC ACTUATOR

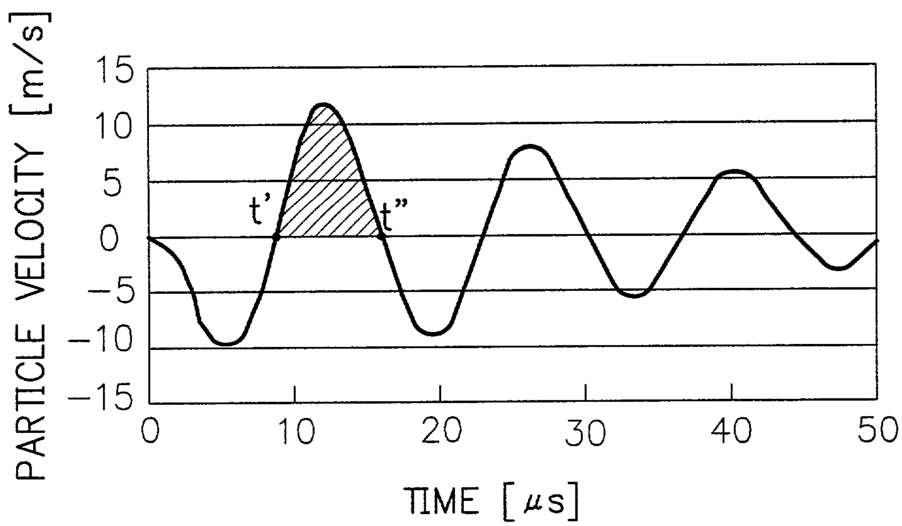
F I G. 4



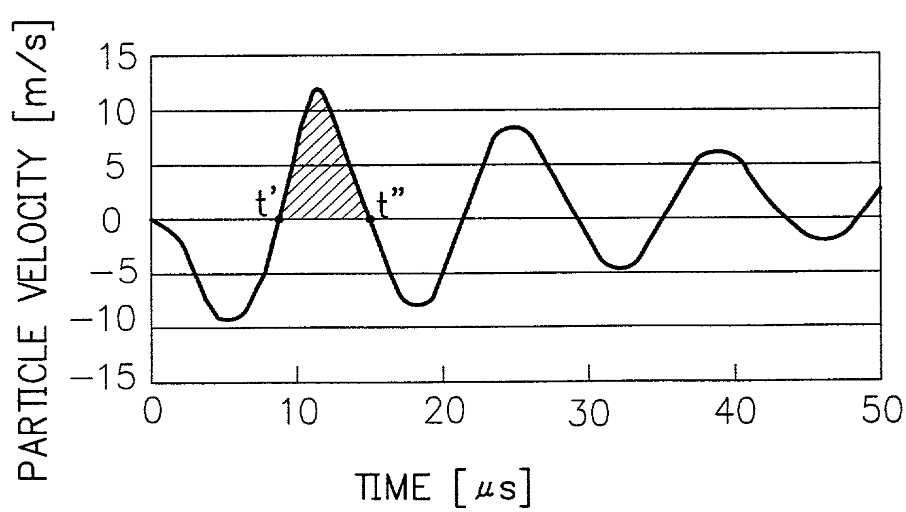
VOLTAGE V
(a)
V1
V2
41
42
43
44
45
TIME t
0
t1
t1'
t2
t2'
t3
t4
VOLTAGE V
(b)
V1
V2
41
42
43
45
TIME t
0
t1
t1'
t2
t3
t4

F I G. 5

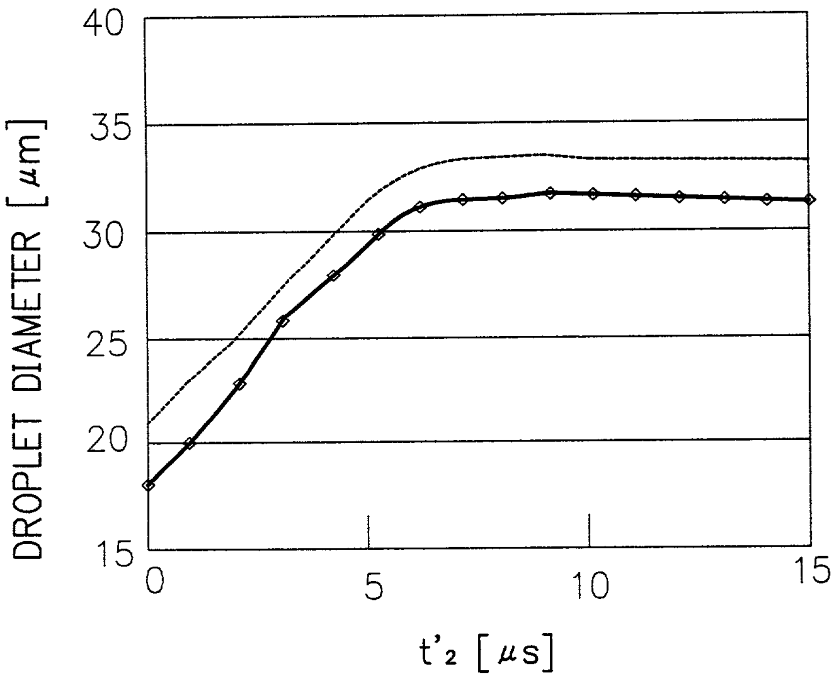
(a)


PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
t'
t"
0
10
20
30
40
50
TIME [μs]

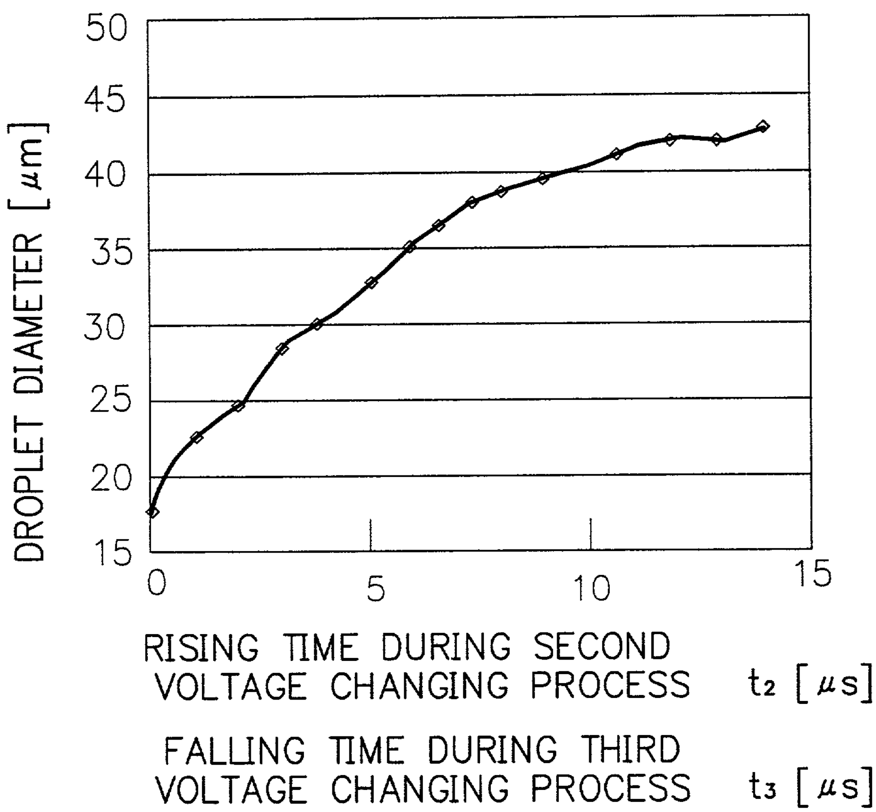
(b)


PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
t'
t"
0
10
20
30
40
50
TIME [μs]

F I G. 6



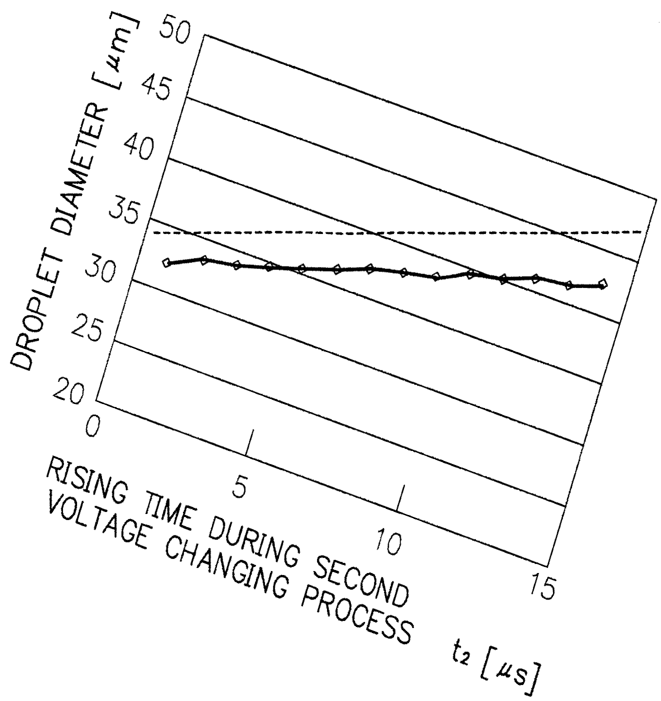
F I G. 7


DROPLET DIAMETER [μm]
50
45
40
35
30
25
20
15
0
5
10
15
RISING TIME DURING SECOND VOLTAGE CHANGING PROCESS t2 [μs]
FALLING TIME DURING THIRD VOLTAGE CHANGING PROCESS t3 [μs]

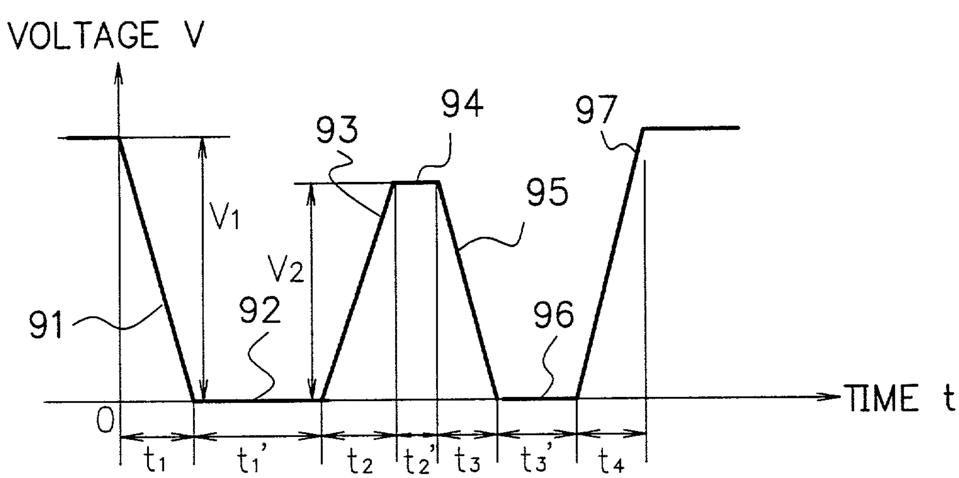
09/807823

8/17

FIG. 8

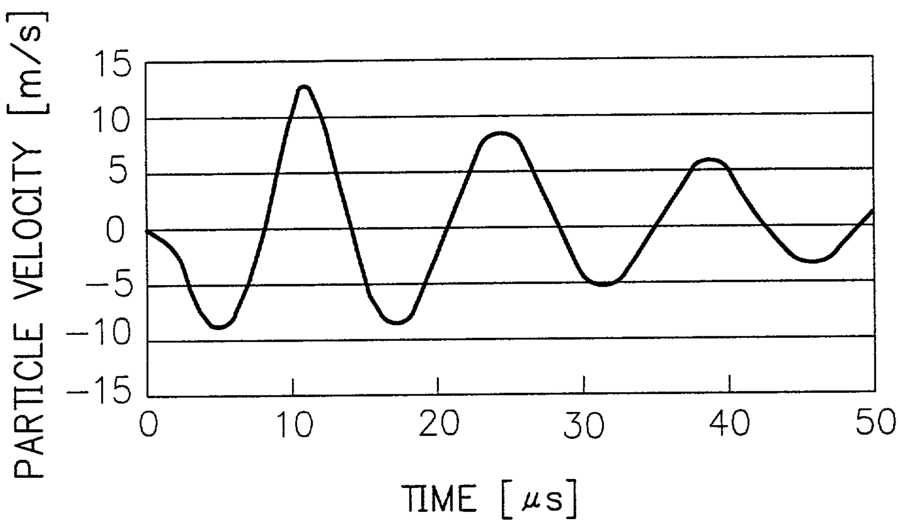


F I G. 9

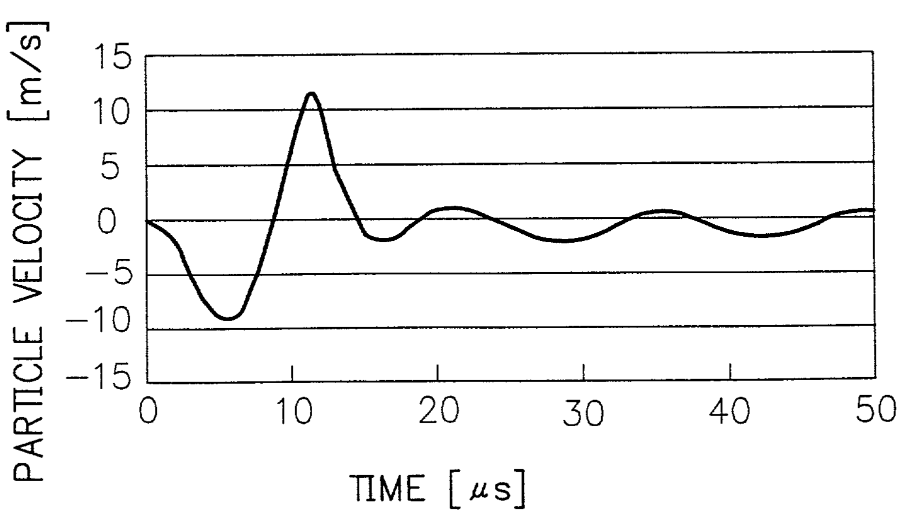


F I G. 10

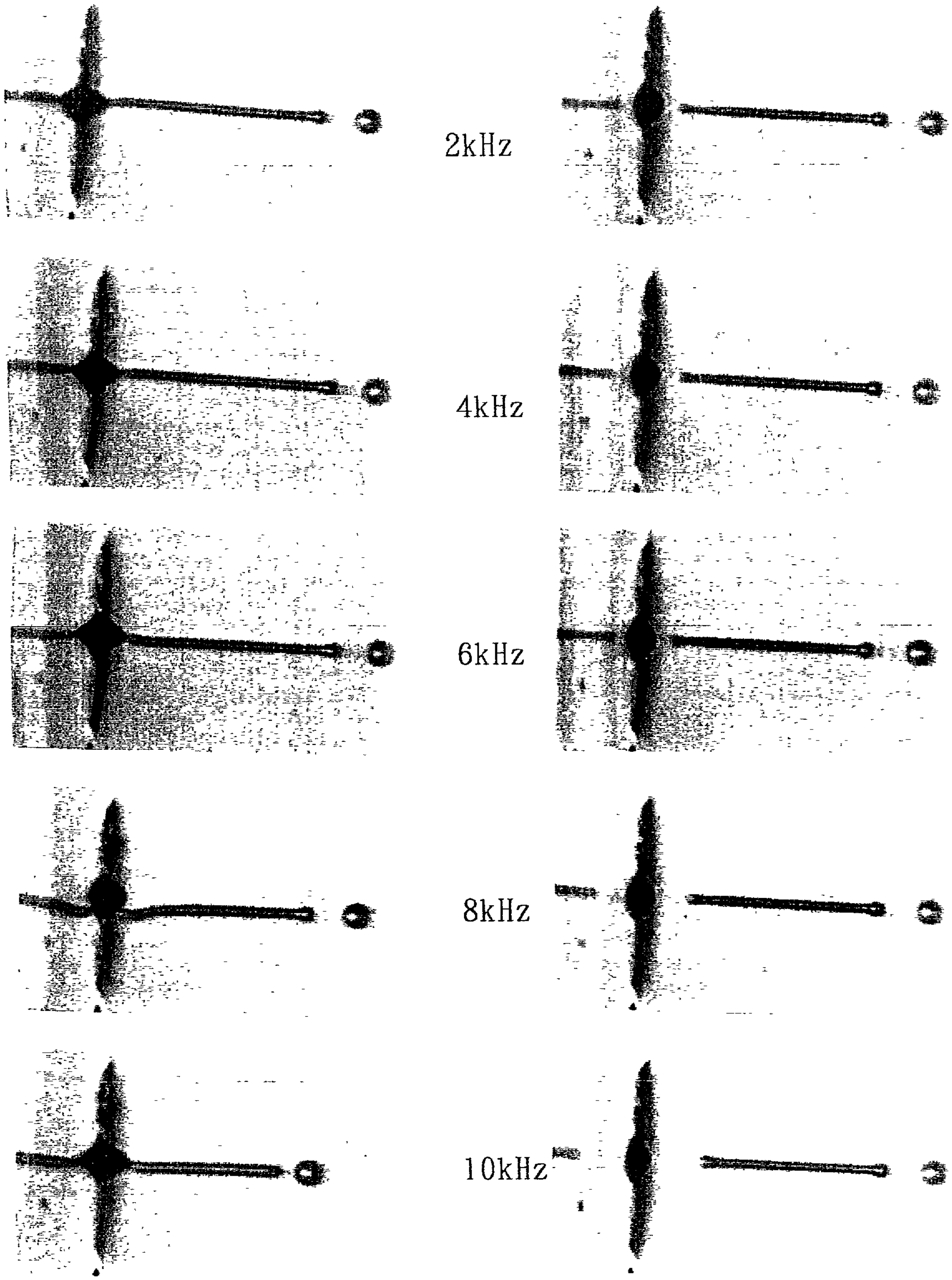
(a)


PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
0
10
20
30
40
50
TIME [μs]

(b)


PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
0
10
20
30
40
50
TIME [μs]

F I G. 11

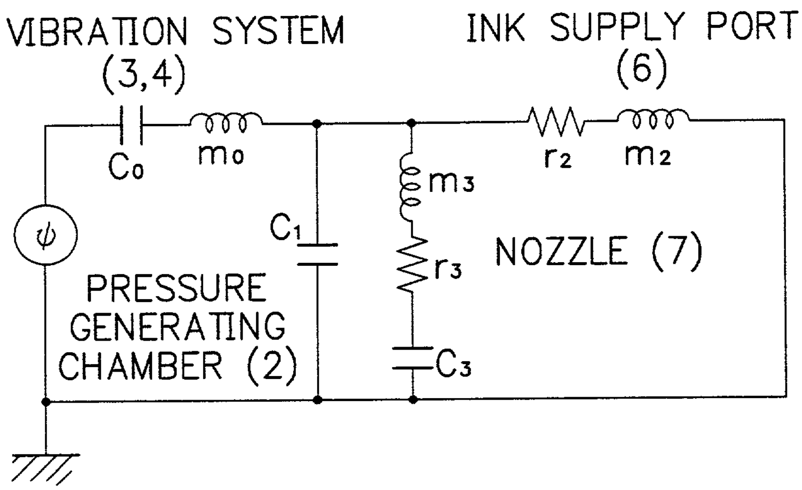


(a) NO RESTRAINT ON REVERBERATION

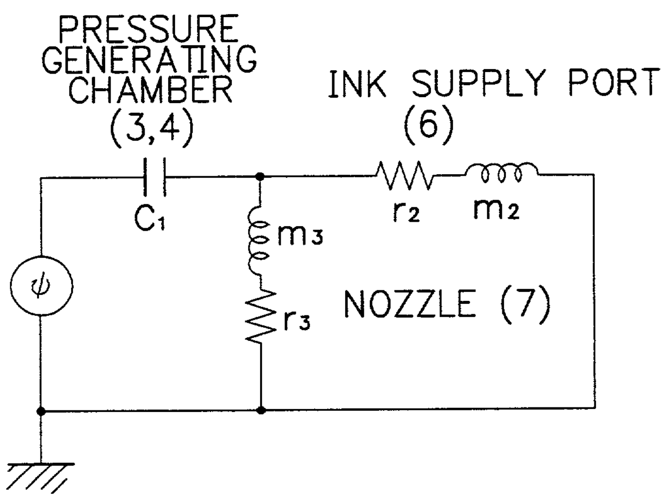
(b) REVERBERATION RESTRAINED

F I G. 12

(a)


VIBRATION SYSTEM
(3,4)
INK SUPPLY PORT
(6)
C0
m0
r2
m2
m3
C1
r3
NOZZLE (7)
PRESSURE
GENERATING
CHAMBER (2)
C3

(b)


PRESSURE
GENERATING
CHAMBER
(3,4)
INK SUPPLY PORT
(6)
C1
r2
m2
m3
r3
NOZZLE (7)

F I G. 13

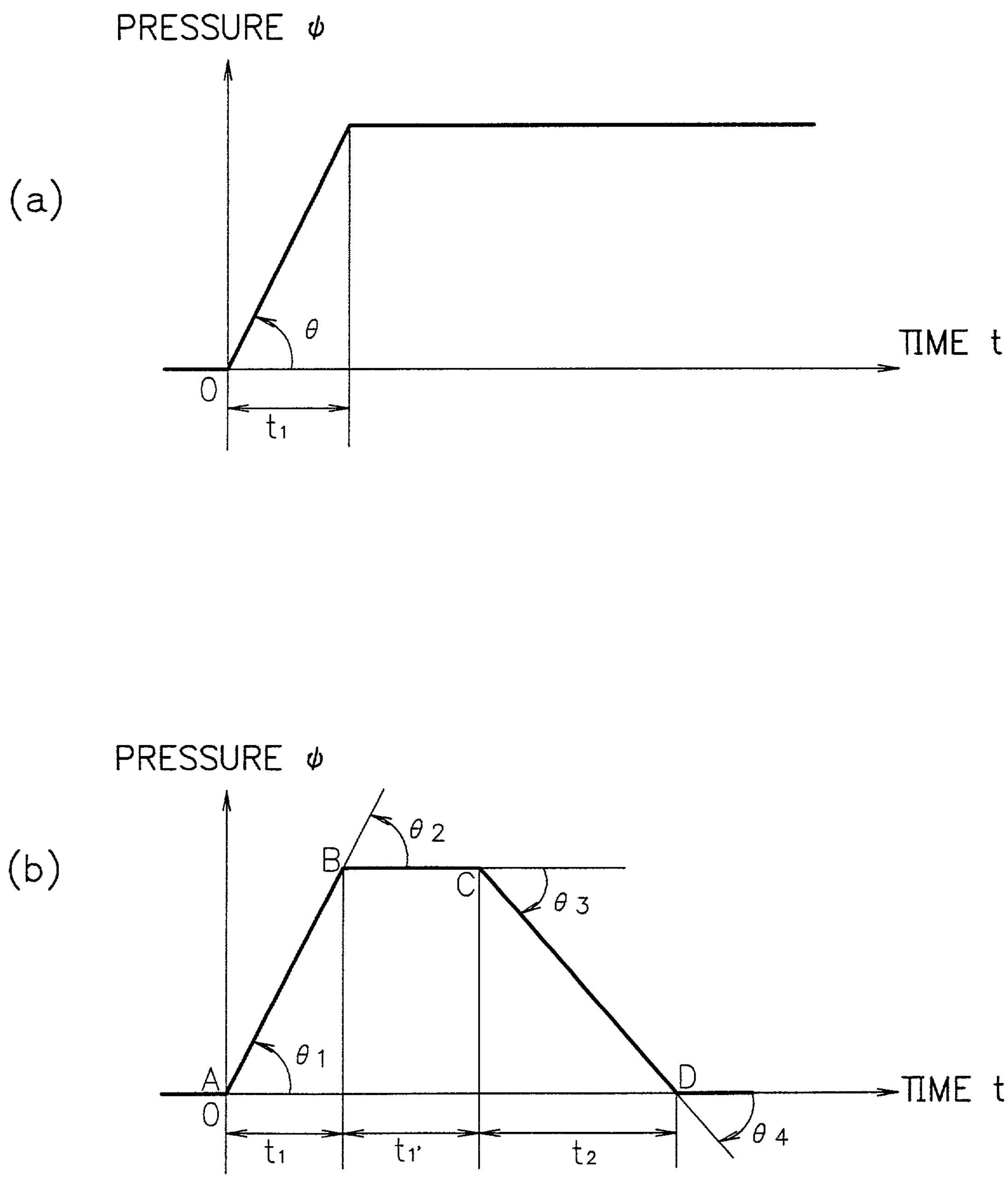
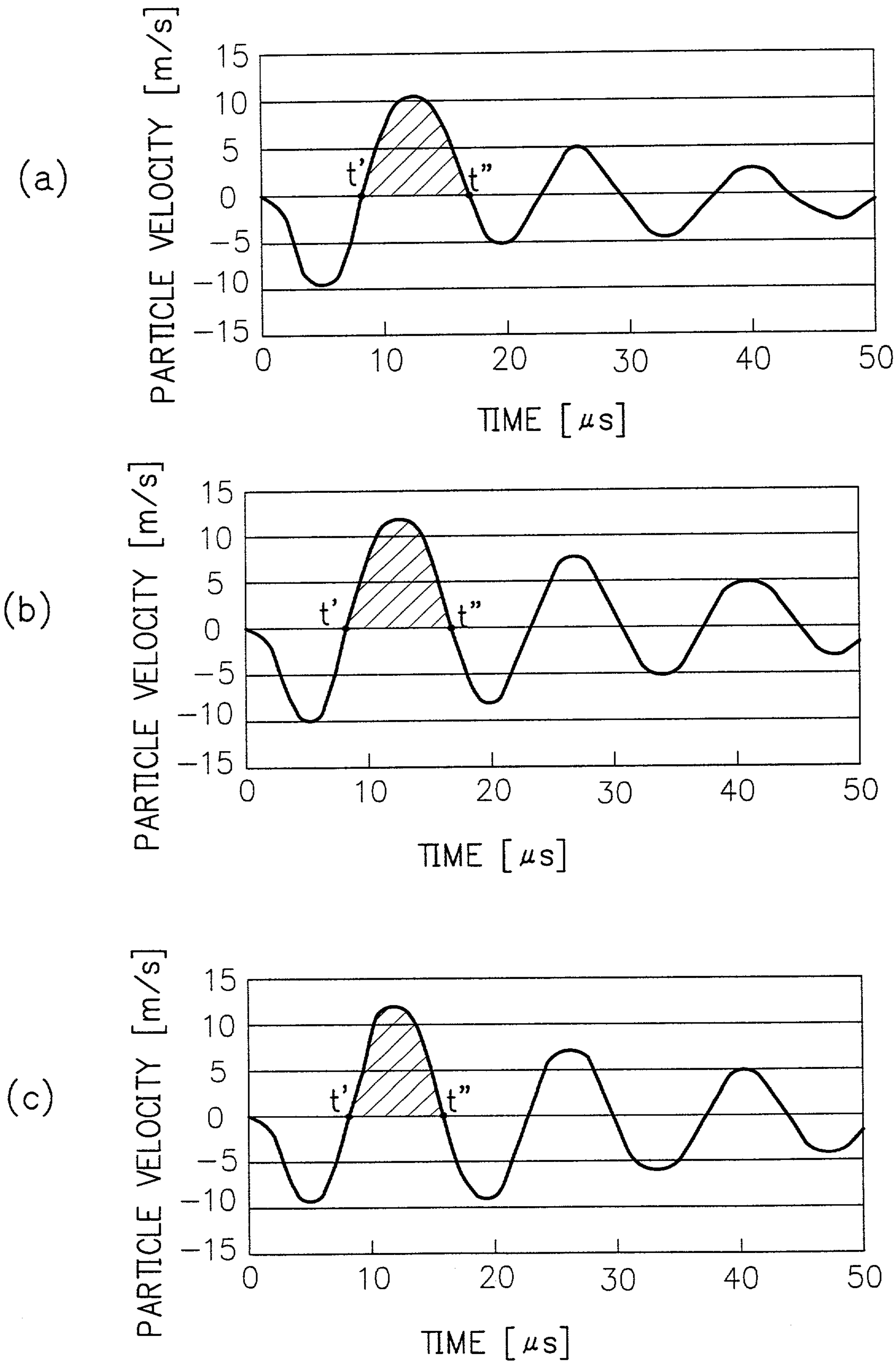
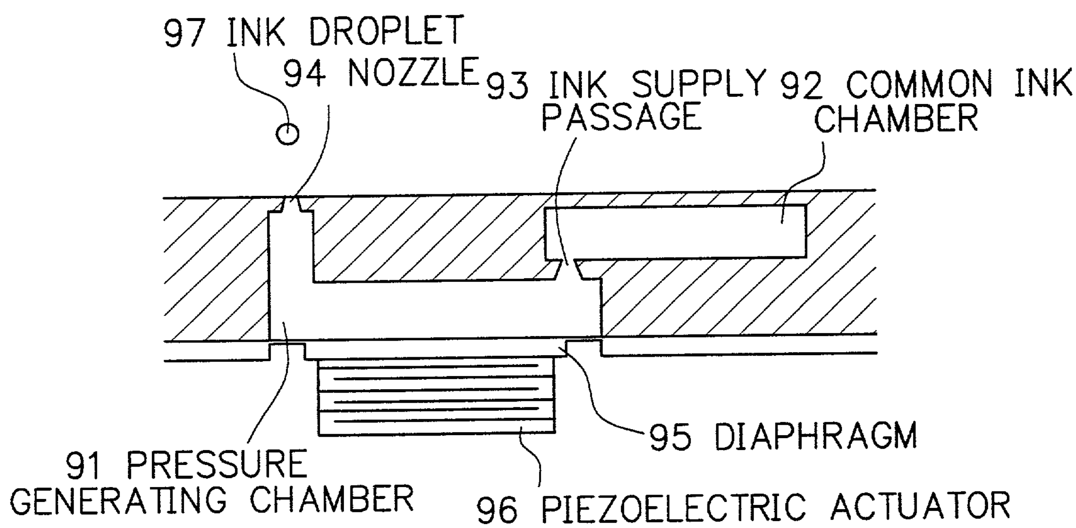

(a)
PRESSURE ϕ
θ
TIME t
0
t_1
(b)
PRESSURE ϕ
θ 2
B
C
θ 3
θ 1
A
D
TIME t
0
θ 4
t_1
$t_{1'}$
t_2

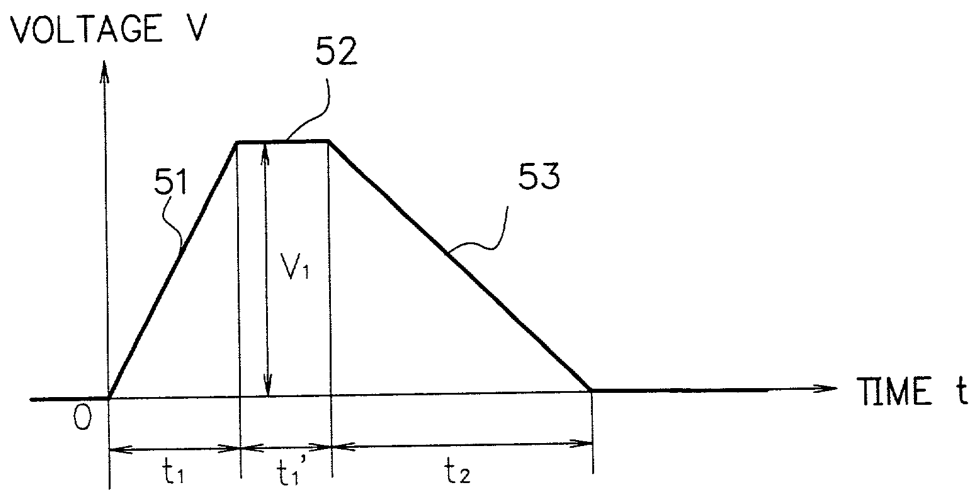
FIG. 14


(a)
PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
t'
t"
0
10
20
30
40
50
TIME [μs]
(b)
PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
t'
t"
0
10
20
30
40
50
TIME [μs]
(c)
PARTICLE VELOCITY [m/s]
15
10
5
0
−5
−10
−15
t'
t"
0
10
20
30
40
50
TIME [μs]

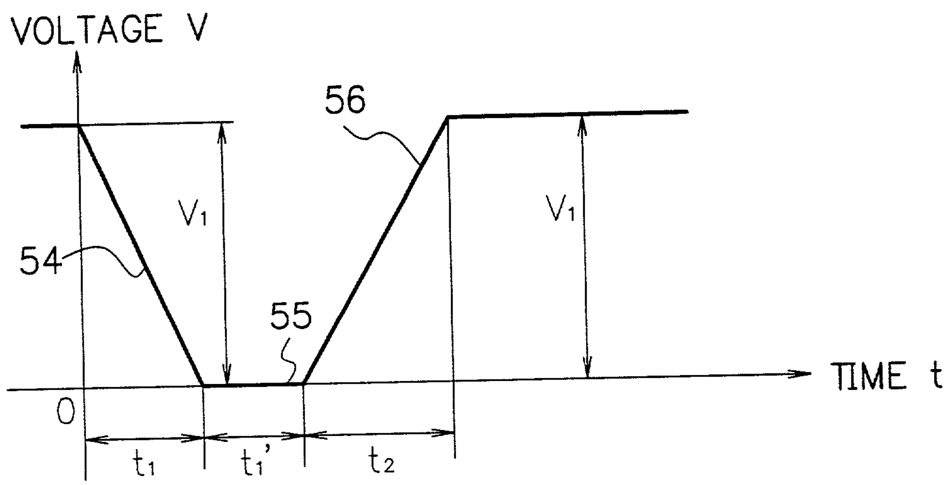
F I G. 15


97 INK DROPLET
94 NOZZLE
93 INK SUPPLY PASSAGE
92 COMMON INK CHAMBER
95 DIAPHRAGM
91 PRESSURE GENERATING CHAMBER
96 PIEZOELECTRIC ACTUATOR

F I G. 16



F I G. 17



Application for United States Patent

DECLARATION AND POWER OF ATTORNEY

As a below named inventor, I hereby declare that:

My residence, post office address and citizenship are as stated below next to my name;

I believe I am the original, first and sole inventor (if only one name is listed below) or an original, first and joint inventor (if plural names are listed below) of the subject matter which is claimed and for which a patent is sought on the invention entitled:
METHOD FOR DRIVING INK JET RECORDING HEAD

the specification of which:
(check one)

___ (is attached hereto)
x was filed on October 14, 1999,
as Application Serial No. PCT/JP99/05678
and was amended on ___________. (if applicable)

I hereby state that I have reviewed and understand the contents of the above identified specification, including the claims, as amended by any amendment referred to above.

I acknowledge the duty to disclose information which is material to the examination of this application in accordance with Title 37, Code of Federal Regulations, § 1.56*

I hereby claim foreign priority benefits under Title 35, United States Code, § 119 of any foreign application(s) for patent or inventor's certificate listed below and have also identified below any foreign application for patent or inventor's certificate having a filing date before that of the application on which priority is claimed:

Prior Foreign Application(s)

(Number)	(Country)	(Day/Month/Year Filed)	priority claimed yes	no
318443/1998	Japan	20/10/1998	x	

I hereby claim the benefit under Title 35, United States Code, § 120 of any United States application(s) listed below and, insofar as the subject matter of each of the claims of this application is not disclosed in the prior United States application in the manner provided by the first paragraph of Title 35, United States Code, § 112, I acknowledge the duty to disclose material information as defined in Title 37, Code of Federal Regulations, § 1.56 which occurred between the filing date of the prior application and the national or PCT international filing date of this application:

(Application Serial No.)	(Filing Date)	(Status: patented, pending, abandoned)

Power of Attorney: As a named inventor, I hereby appoint Sean M. McGinn, Reg. No. 34, 386, and Frederick W. Gibb, III, Reg. No. 37,629, as attorneys and/or agents to prosecute this application and transact all business in the Patent and Trademark Office connected therewith. All correspondence should be directed to **McGinn & Gibb, PLLC, 8321 Old Courthouse Road, Suite 200, Vienna, Virginia 22182-3817**. Telephone calls should be directed to McGinn & Gibb, PLLC at (703) 761-4100.

I hereby declare that all statements made herein of my own knowledge are true arid that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code and that such willful false statements may jeopardize the validity of the application or any patent issued thereon.

Full Name of Sole or First Inventor MASAKAZU OKUDA

Inventor's Signature *Masakazu Okuda* Date March 28, 2001

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Citizenship Japanese

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Full Name of Second Joint Inventor, If Any

Inventor's Signature Date

Residence

Citizenship

Post Office Address

Full Name of Third Joint Inventor, If Any Date

Residence

Citizenship

Post Office Address

Full Name of Fourth Joint Inventor, If Any Date

Residence

Citizenship

Post Office Address

(An additional sheet(s) is/are attached hereto if the present invention includes more than four inventors.)

*Title 37, Code of Federal Regulations, § 1.56:

(a) A patent by its very nature is affected with a public interest. The public interest is best served, and the most effective patent examination occurs when, at the time an application is being examined, the Office is aware of and evaluates the teachings of all information material to patentability. Each individual associated with the filing and prosecution of a patent application has a duty of candor and good faith toward the Patent and Trademark Office, which includes a duty to disclose to the Office all information known to that individual to be material to patentability as defined in this section. The duty to disclose information exists with respect to each pending claim until the claim is canceled or withdrawn from consideration, or the application becomes abandoned.

(b) Under this section, information is material to patentability when it is not cumulative to information already of record or being made of record in the application, and (1) it establishes by itself or in combination with other information, a prima facie case of unpatentability; or (2) it refutes, or is inconsistent with, a position the applicant takes in: (i) opposing an argument of

unpatentability relied on by the Office, or (ii) asserting an argument of patentability.